www.itcon.org - Journal of Information Technology in Construction - ISSN 1874-4753

MULTIUSER IMMERSIVE VR VERSUS BIM PLATFORMS FOR REMOTE AEC TEAM COLLABORATION

SUBMITTED: August 2025
PUBLISHED: March 2025
EDITOR: Žiga Turk
DOI: 10.36680/j.itcon.2026.013

Bita Astaneh Asl, Assistant Professor
School of Engineering, California State University, East Bay
bita.astanehasl@csueastbay.edu

Tanmay Z. Tuscano, Master's Student
School of Engineering, California State University, East Bay
tanmaytuscano@gmail.com

Ankith Prasad Muralidhar Sathyanarayana, Master's Student
School of Engineering, California State University, East Bay
ankith.prasad1998@gmail.com

SUMMARY: *Advancements in immersive virtual reality (VR) raise new possibilities for multidisciplinary architecture, engineering, and construction (AEC) team collaboration; however, the empirical basis for assessing its effectiveness remains insufficiently examined. This paper investigated whether avatar body language and 3D markup tools in a head-mounted display (HMD) VR platform improve remote AEC team performance compared to a Building Information Modeling (BIM) platform configured with equivalent navigation and communication features. A controlled counterbalanced experiment was conducted with ten teams, using a mixed-methods evaluation framework that incorporated meeting duration, decision-reporting accuracy, participant feedback, and observational analysis. The results showed that immersive VR significantly reduced average meeting duration by 26.7% and improved final decision-reporting accuracy compared to the BIM platform, while qualitative findings indicated that avatar embodiment and visual collaboration tools supported more effective coordination. These findings inform technology adoption decisions for AEC practitioners and advance the empirical foundation for researchers evaluating immersive VR as a coordination platform for distributed project teams. They further motivate future research aimed at refining immersive collaboration features and advancing their systematic evaluation to support evidence-based integration into AEC practice.*

KEYWORDS: *HMD VR, multiuser, BIM, multidisciplinary teams, remote collaboration, avatar.*

REFERENCE: *Astaneh Asl, B., Tuscano, T. Z., & Muralidhar Sathyanarayana, A. (2026). Multiuser immersive VR versus BIM platforms for remote AEC team collaboration. Journal of Information Technology in Construction (ITcon), 31, 301-331. https://doi.org/10.36680/j.itcon.2026.013*

1. INTRODUCTION

Multidisciplinary architecture, engineering, and construction (AEC) collaboration is a cornerstone of successful project delivery (Muthumanickam et al, 2023). As project teams become increasingly distributed, the AEC industry continues to adopt digital collaboration platforms that support remote coordination, even for local projects, allowing stakeholders to collaborate efficiently without co-location (Rafsanjani and Nabizadeh, 2023). Building Information Modeling (BIM) platforms have emerged as widely adopted tools to support remote collaboration by enabling stakeholders to share, review, and coordinate model-based project information from any location (Sacks et al, 2018). However, conventional screen-based meetings conducted through videoconferencing tools often fail to replicate the embodied interaction, spatial immersion, and nonverbal communication cues that support mutual understanding and effective team coordination in co-located settings (Kim et al, 2020).

Immersive virtual reality (VR), particularly through head-mounted displays (HMDs), has gained increasing attention in the AEC industry for its ability to simulate physical presence within digital spaces, enabling new approaches to design review, project coordination, and stakeholder engagement (Wen and Gheisari 2020, Zhang et al, 2020). Unlike screen-based BIM platforms, immersive VR enables users to navigate and interact with building models while engaging with teammates through avatars and built-in collaboration tools, such as laser pointers and markup features, within a shared, immersive environment (Ververidis et al, 2022). To explore the potential of immersive technologies in supporting distributed project teams, this paper compares immersive VR and BIM platforms in a remote setting for multidisciplinary AEC team collaboration.

1.1 Literature review

The following literature review is organized to provide background on AEC team practices, describe different types of model-based collaboration platforms, and summarize prior research on the use of immersive VR and BIM platforms for design review and coordination. It also examines how specific platform features, such as avatar interaction, visual collaboration tools, and spatial immersion, affect team communication and collaborative decision-making.

1.1.1 Model-based platforms for AEC team collaboration

Before the adoption of digital coordination tools, full-scale physical mockups were widely used to support multidisciplinary collaboration in AEC projects. These mockups allowed project stakeholders to engage with design proposals at a human scale, offering an opportunity to evaluate constructability, spatial relationships, accessibility, and operational workflows. While highly effective for uncovering design ambiguities and installation conflicts, physical mockups are also resource-intensive, time-consuming to build, and often inflexible in accommodating design changes (Pietroforte and Tombesi, 2010). As the complexity and pace of construction projects increased, the AEC industry turned to model-based digital platforms as more scalable, cost-effective tools to facilitate coordination.

Today, a variety of digital platforms are available to support multidisciplinary collaboration in AEC projects. These platforms differ in how they represent the model, allow users to interact, and support communication during team coordination. Five primary collaboration platforms are commonly discussed in the literature: face-to-face BIM, remote BIM, projected VR, three degrees of freedom (3DOF) HMD VR, and six degrees of freedom (6DOF) HMD VR. In 3DOF systems, users can rotate their head to look around, but they remain fixed in a single location. In contrast, 6DOF systems allow users to move freely in physical space, enabling not only head rotation but also translation along the X, Y, and Z axes. The descriptions of these five platforms in this section are based on the comparative analysis presented in Astaneh Asl et al. (2023b), which evaluated them based on features known to influence AEC team collaboration, such as model presentation, viewpoint control, availability of visual communication tools, particularly pointer and markup tools, and the fidelity of verbal and nonverbal communication, including facial expression, body language, and voice direction.

Face-to-face BIM is the most common method of AEC collaboration, where team members meet in person to view a shared model, typically projected onto a 2D screen. This setup enables access to rich non-verbal communication, such as facial expressions, body language, and directional voice, all of which support team awareness and speaker recognition. However, it offers a non-immersive experience, and only one person, usually the BIM coordinator, has control over the model viewpoint and markup tools. Other participants must passively follow the shared display, which limits concurrent interaction and active contribution. Remote BIM replicates the face-to-face model using videoconferencing tools, allowing geographically distributed teams to collaborate. The shared model is still viewed on a 2D screen, and control remains limited to one person at a time. While remote BIM removes location constraints and increases meeting flexibility, it also reduces communication richness. Directional voice is lost, and body language and facial expressions are only partially visible, depending on whether cameras are on. Markup tools exist but are constrained to either the BIM program interface or the conferencing platform, with annotations created as 2D overlays on a shared view.

Projected VR systems immerse participants in a large physical space where the model is projected onto multiple surfaces, typically the sides of a cube-shaped room or curved screens. This environment preserves full body language and facial expressions, and directional voice. However, only one user can interact with the model at a time with 6DOF movement, while others are limited to passive observation with 3DOF perspectives. These systems are expensive, physically restrictive, and lack widely available digital markup tools. 3DOF HMD VR can present the model as a 360-degree spherical image, enabling users to explore the environment through head rotation from a fixed point at the center of the sphere. Users have their own viewpoint, along with access to individual pointer and markup tools, which can be used to annotate the model as 2D overlays on the image. This platform supports remote participation, but it lacks full-body movement, directional audio, and capturing facial expressions and body language. 6DOF HMD VR offers the most advanced immersive experience, allowing users to move freely in a 3D digital environment and interact with one another as avatars. Each participant has full 6DOF navigation, their own viewpoint, and individual access to pointer and markup tools capable of creating 3D annotations in the 3D digital space. While current commercial platforms cannot capture facial expressions, full body language, and directional audio simulation, 6DOF HMD VR is capable of providing them in the future.

1.1.2 BIM for design review and coordination

BIM offers a model-based environment that improves spatial comprehension compared to traditional 2D drawings, which facilitates multidisciplinary AEC collaboration and supports more integrated project workflows (Eastman et al, 2011). Within these workflows, design review is typically led by the design team, with limited involvement from the construction team. BIM-based design reviews often improve communication and reduce misunderstandings compared to traditional 2D drawings (Sacks et al, 2018). These reviews also serve as opportunities to engage project stakeholders in providing feedback and validating design, construction, and operational aspects of the project (Messner et al, 2021).

The coordination process, on the other hand, focuses on the integration of building systems, such as structural, mechanical, electrical, and plumbing (MEP), and is typically led by the construction team with involvement of the design team (Sacks et al, 2018). Coordination aims to support multidisciplinary decision-making by identifying and resolving system conflicts early in the process, thereby improving constructability and minimizing rework (Fischer, 2006, Liston et al, 2010). Historically, coordination relied on manually comparing 2D drawings and often overlaying them using transparent sheets or light tables, to identify conflicts between building systems, and was reviewed frequently in in-person meetings (Tatum and Korman, 1999). This process was time-consuming, difficult to visualize, and prone to oversight, often resulting in undetected clashes that required costly resolution during construction (Korman et al, 2003, Liston et al, 2010).

BIM has transformed coordination by enabling the integration of discipline-specific 3D models into a federated model, allowing teams to identify conflicts earlier and collaborate more effectively. This model-based approach has been shown to improve coordination efficiency, reduce rework, and support more informed decision-making across project teams (Khanzode et al, 2008, Staub-French and Khanzode, 2008). While BIM significantly enhances AEC team collaboration, challenges remain in remote and distributed settings, where communication may become fragmented and spatial understanding is often limited when team members rely on screen-sharing without a shared immersive collaboration environment (Heinonen et al, 2022, Wu et al, 2024).

1.1.3 Immersive VR for design review and coordination

Since immersive VR can simulate the spatial and visual conditions of a facility, it supports design reviews that may reduce or replace the need for physical mockups, offering potential cost and time savings (Messner et al, 2021). Consequently, several studies have compared virtual mockups with physical mockups to evaluate the potential of VR as a substitute. Most of these studies used projected VR systems, with findings suggesting that fully immersive environments such as CAVE systems (Cruz et al 1992) are more appropriate for smaller groups seeking higher levels of immersion, while semi-immersive systems projected on curved screens are more suitable for larger groups (Castronovo et al, 2013). The larger footprint of these systems also provides space for incorporating other visualization media, such as drawings and digital models, to support more effective discussions and improve meeting efficiency (Liu et al, 2020).

These comparative studies have mainly focused on evaluating end-user feedback during design reviews. Majumdar et al. (2006) and Maldovan et al. (2006) compared courtroom designs using projected VR mockups against full-scale plywood mockups. Majumdar et al. (2006) found that VR reduced decision-making time by over 50% due to real-time design updates compared to the physical mockup. Maldovan et al. (2006) reported that VR helped users effectively assess sightlines from multiple viewpoints. Similarly, Westerdahl et al. (2006) compared a virtual office mockup to the completed building and found that participants found the VR model helpful for the design decision-making process. Kuliga et al. (2015) also found that users' evaluations of a real building and a high-fidelity virtual mockup were closely aligned, though participants noted missing atmospheric details. Although virtual mockups support design evaluations, participants in these studies, particularly in Wahlström et al. (2010), noted limitations in perceiving dimensions and spatial sufficiency, indicating that projected VR systems may not fully replicate the physical experience.

Recent literature shows that improvements in HMD hardware have significantly enhanced dimension perception accuracy over time (Feldstein et al, 2020); however, no current commercially available devices fully replicate the dimensional perception of the physical environment (Kelly, 2022). In addition, tactile technologies remain largely absent from design review practices, limiting the ability to assess materiality or physical fit (Lu et al, 2022). As a result, a recent study comparing a physcial hotel room mockup with an HMD-based virtual model for design review found that AEC professionals did not yet consider immersive VR fully capable of replacing physical mockups. Instead, they recommended its use for early design review and coordination for technical AEC team collaboration, given the current technological capabilities (Astaneh Asl and Dossick, 2024).

While immersive VR has not been viewed as a full substitute for physical mockups, studies show that it improves the dimension perception (Paes et al, 2021) and spatial understanding of architectural (Azarby and Rice, 2022), structural (Fogarty et al, 2018), and MEP systems (Astaneh Asl et al, 2026) compared to the BIM platforms that present 3D models on 2D screens. This perceptual advantage has contributed to the prominence of design review as the most frequently studied application of immersive VR in AEC communication workflows (Wen and Gheisari, 2020, Zhang et al, 2020, Wu et al, 2024). While most existing studies using HMD VR focus on individual experiences, such as Heydarian et al (2015) and Bhonde et al (2022), or involve only one participant immersed in VR while others join passively through non-immersive platforms, such as Rigutti et al (2018) and Wolfartsberger (2019), only a limited number of studies have investigated AEC team collaboration (Prabhakaran et al, 2022).

Du et al. (2016, 2018a, 2018b) progressively developed and tested a cloud-based multi-user immersive VR system to support remote AEC team collaboration. Early implementations introduced a shared green marker tool, functioning as an annotation tag to highlight specific objects or areas in the model, which helped improve group focus and communication during distributed walkthroughs. It integrated avatar embodiment and later included individual laser pointers, allowing users to highlight elements independently. Experiments showed that multiuser VR significantly improved inspection task performance compared to single-user VR. Abbas et al. (2019) compared immersive VR to a face-to-face BIM platform for design tasks. While VR matched the BIM platform in discussion quality and richness, it fell short in communication appropriateness and accuracy due to limited nonverbal cues. The study emphasized the need to improve human interaction features, such as facial expressions and gestures, in VR to support effective collaboration.

Tea et al (2022) demonstrated that multiuser immersive VR environments with avatars equipped with laser pointers significantly improved the detection of missing and misplaced components during remote collaborative design review, with the VR group identifying 21.5% more discrepancies than the group in the BIM platform. Sateei et al (2022) explored in-person multi-user immersive VR design reviews in an elementary school project. The system included measurement, markup, and screenshot tools, which participants actively used during collaborative walkthroughs. Users were represented as avatars in the shared VR space. The study found VR platform effective for both small-scale and full-scale design evaluation by enabling transitions between miniature and immersive views. Sateei et al. (2025) examined two real-world healthcare design projects in a multi-user VR setting to assess how interactive features affect end-user involvement. Participants collaboratively explored layouts through avatar-based interaction and object manipulation, which enhanced engagement and active co-design.

Beyond design review, immersive VR also shows promise in supporting coordination processes, where multiple disciplines must resolve complex spatial and systems-based conflicts. Despite the automation and early clash detection capabilities of BIM tools, the resolution of system conflicts in the coordination process still relies on active and structured collaboration among project stakeholders (Mehrbod et al, 2019). Studies show that AEC professionals often draw building components to communicate issues and propose solutions (Dossick and Neff, 2011), a process that relies on the accurate recall of design details and spatial configurations (Scrivener et al, 2000). Immersive VR has been shown to improve recall of both architectural layouts (Tüker and Tong, 2021) and MEP systems (Astaneh Asl et al, 2023a), suggesting that it may enhance users' ability to remember coordination decisions and articulate them more effectively through sketches, markups, or collaborative discussion. As coordination often spans multiple sessions, the ability to maintain spatial memory and continuity may be critical to improving communication efficiency and decision accuracy in immersive environments.

While studies show that many issues identified in the field had been overlooked during BIM coordination (Alsuhaibani et al, 2022), immersive VR has demonstrated potential to improve the identification and reporting of such issues by enabling AEC professionals to detect missing components and constructability problems more effectively (Girgin et al, 2024, Johansson and Roupé, 2024). Shi et al (2016) conducted one of the early studies on remote team collaboration for coordination. It included avatars with laser pointers for a team of two participants, a designer, and a facility manager, to discuss MEP issues in facility management coordination. The study demonstrated VR's potential for improving communication efficiency. Zaker and Coloma (2018) later conducted a study with two professionals, BIM modeler and MEP installer, co-located in the same space, to evaluate the model for MEP coordination and space check for maintenance. The participants found the platform useful for coordination and suggested including a markup tool for more efficient collaboration.

Recent studies have highlighted the use of visual cues, such as pointers and markups, as essential tools for collaboration in VR environments (Wu et al, 2024). Truong et al. (2021) conducted a case study on the remote coordination of elevator machine rooms. The platform featured avatars equipped with measurement and 3D markup tools, and the tasks included constructability assessment, system conflict detection, access checks, and layout planning. The study demonstrated that these collaborative tools enabled AEC professionals to identify clearance issues, installation conflicts, and routing challenges more effectively than conventional methods. Haahr and Knak (2023) simulated in-person AEC collaboration using multi-user VR for both design review and coordination tasks, employing avatars equipped with comprehensive collaboration tools, including 3D markup, measurement, and issue-tracking features. The results showed that immersive VR improved the review efficiency, with participants requiring less time per issue identified than in the BIM platform. Johansson and Roupé (2024) studied the application of immersive VR for real-world projects, exploring multiuser experiences across in-person and remote settings for design review, coordination, and planning tasks in small-scale and full-scale views. The system provided comprehensive collaboration tools, including pointer, 3D markup, and measurement features. Based on user feedback and observational data, the study found that multi-user immersive VR supported spatial understanding, facilitated communication, and enhanced focused collaboration. Spatial cues like avatar position, gaze, and pointing were sufficient to create a strong sense of presence in remote VR collaboration, without the need for highly realistic avatars.

While immersive VR enhances presence and engagement through avatars and spatial interaction (Zhang et al, 2020, Dey et al, 2024), there is a gap in the literature for team process and coordination frameworks (Zhang et al, 2020, Wu et al, 2024), with a clear need for structured empirical studies to evaluate how it integrates with BIM-based workflows (Zhang et al, 2020, Balin et al, 2023, Wu et al, 2024). Most research has focused on prototype development or exploratory case studies emphasizing perceived benefits and user experiences, with limited empirical evidence comparing multi-user VR environments to BIM platforms. Notably, no prior study has conducted a controlled experiment to assess the impact of avatar body language and 3D markup tools in immersive VR versus the remote BIM platform. This lack of comparative research motivated the present paper.

1.2 Research objectives

This paper was built upon the research by Astaneh Asl and Dossick (2022), which examined the efficiency of AEC team collaboration using two platforms: 3DOF HMD VR and BIM in the remote coordination process. In the 3DOF HMD VR platform, the spaces in the model were presented as 2D spherical 360-degree images. Users were fixed at the center of each sphere and could explore the environment through head rotation, with the ability to teleport between spaces. The platform provided individual color-coded pointers and markup tools with annotations created as 2D overlays on the spherical image. The BIM platform was similarly configured with 3DOF constraints, restricting users to fixed locations and allowing markups created as 2D annotations on the screen view. The study employed a controlled experimental design to isolate two variables of VR's immersive environment and markup tool capabilities to assess their impact on team collaboration efficiency. The findings indicated that teams spent less time in the VR environment to reach a shared understanding of the problem resolution compared to the BIM platform, and that VR markups were more efficient for team communication. However, some team members became disoriented in the 360-degree VR environment, as they were unable to perceive where others were looking, pointing their pointer, or creating markup, which impaired their ability to follow the team's conversation and, in some cases, led to inaccurate reporting of the final team decision. In both platforms, markup was limited to 2D annotations, either on model views or 360-degree images, which constrained participants' ability to communicate spatial relationships effectively.

Astaneh Asl and Dossick (2022) recommended a study using 6DOF HMD VR to investigate whether the avatar body language and 3D markups could mitigate the disorientation challenges observed in 3DOF HMD VR and enhance AEC team collaboration during remote coordination. The present paper responds directly to that recommendation through a controlled experiment designed to isolate and evaluate the impact of these features on team performance. The paper employed a mixed-methods evaluation framework incorporating both objective and subjective measures. Objective evaluation criteria were grounded in the performance model proposed by O'Donnell and Duffy (2002), which conceptualizes performance as a function of both efficiency and effectiveness. Efficiency is defined as the productivity of the team process, measured by the amount of output generated relative to time and effort. Effectiveness, on the other hand, is defined as the extent to which team outcomes align with the intended goals of the task. Accordingly, the objective evaluation included the total duration of each meeting to assess efficiency and the consistency of individual responses with the group's final design outcome to assess effectiveness. Subjective evaluation aimed to capture participants' reflections on the usability and effectiveness of each platform, collected through post-meeting questionnaires and a final comparative assessment. In addition, the experiment was structured to support qualitative analysis through observation of team interactions, enabling the research team to examine communication dynamics and the use of avatar body language and visual collaboration tools. The novelty of this paper lies in the overall experimental design, which combines controlled conditions, feature isolation, and mixed-method evaluation within a single comparison that extends beyond how platform features and team collaboration are typically examined in prior studies. The objective of this paper was to evaluate how avatar body language and 3D markup capabilities in a 6DOF immersive VR platform influence remote multidisciplinary AEC team collaboration in the coordination process, compared to a BIM platform with matched navigation and communication features.

Table 1: Platform features implemented in the experiment.

Feature	BIM Platform	VR Platform
Participant Experience	Non-immersive	Immersive
Degrees of freedom	Six degrees of freedom (6DOF)	Six degrees of freedom (6DOF)
Facial Expression	Not available	Not available
Body Language	Not available	Partially available using avatars
Pointer & Markup Tools	Individual tools	Individual tools
Markup Presentation	2D annotation on a 2D screen	3D annotation in a 3D digital environment

2. RESEARCH METHOD

A controlled experiment was designed to compare AEC team performance for remote coordination in two platforms of 6DOF HMD VR and BIM. To isolate the effects of immersive VR's avatar body language and 3D markup capabilities, both platforms were configured to provide similar navigation and features for team communication, as summarized in Table 1 and further detailed in section 2.3, Physical and Digital Setup. The experimental design assumed that teams would exhibit different interaction dynamics and that individual participants would vary in communication styles and problem-solving approaches. Consequently, team performance was not assumed to be directly comparable across teams. Accordingly, two comparable scenarios were developed that allowed teams to collaborate in both platforms, with half of the teams starting in the VR platform and half starting in the BIM platform, creating a counterbalanced experimental design. Participants were grouped into teams of three, with the roles of architect, structural engineer, and contractor. They were provided role-specific technical information and were asked to collaborate solely based on the given technical knowledge. Teams were asked to exchange their technical information and then collaborate to propose an alternative design that meets the technical constraints of all team members. Data for this paper were collected through observation and questionnaires. The following sections of 2.1. Participants, 2.2 Scenarios, 2.3 Digital and Physical Setup, 2.4 Questionnaires, and 2.5 Experiment Procedure provide detailed information about the experiment.

2.1 Participants

The experiment participants were thirty California State University, East Bay (CSUEB) graduate students enrolled in the graduate-level course CMGT 610 – BIM and Advanced Technologies in the School of Engineering's Construction Management program. Participants' demographic and background information, including age, bachelor's degree, AEC industry experience, and prior experience with BIM and VR, was collected to assist in forming comparable teams and minimizing the potential influence of prior experience on the results. Participants ranged in age from 22 to 35 years, with an average age of 25.5. They self-identified as 30% female and 70% male. Of the participants, 50% held bachelor's degrees in civil engineering, 36.7% in architecture, and 13.3% in non-AEC fields. Thirty percent reported no industry background, and the remaining 70% had industry experience ranging from a three-month summer internship to five years, with an average of 1.7 years among those with prior experience. All participants holding a non-AEC bachelor's degree had industry experience. Thirty percent of participants had previous experience with 3D modeling. The majority had no prior exposure to VR, while 16.7% reported having used it a few times, and only 6.7% had substantial experience, primarily through gaming.

Before the experiment, participants were trained on BIM for seven weeks with hands-on lab activities, with a main focus on model navigation, design review, and 3D coordination. During this period, teams were given a final project that required them to get to know each other, work in a team setting, and build a team relationship. At the time of the experiment, participants had completed the design review and 3D coordination portion of their final project. Participants were also trained on model navigation and markup creation in VR, as well as the use of screen-sharing and markup tools within the video conferencing platform, through video tutorials and a hands-on practice session conducted prior to the experiment. It is important to note that the experiment had two more teams that were excluded due to ineligibility. One team had a member who felt dizzy during the VR meeting and had to withdraw from the session. One participant was unable to wear the VR headset due to large-frame eyeglasses, although the spacer was installed on the headset.

2.2 Scenarios

Two comparable scenarios of A and B were developed with the same number and type of technical constraints based on a hypothetical research facility. In Scenario A, the Lab and the mechanical room containing boilers and an air handler were located on the first floor, where the duct and pipes ran horizontally to serve the Labs. In Scenario B, the mechanical room and the Lab were located at two different levels, where the duct and pipes ran vertically. The details of both scenarios are as follows.

2.2.1 Scenario A

In Scenario A, a portion of the southern zone of the research facility was presented to the participants, as illustrated in Figure 1.a. Participants were assigned role-specific technical constraints and were instructed to communicate the following constraints to one another during the collaborative session.

Structural constraints: The structural engineer was instructed to inform the team that the East wall of the mechanical room and the adjacent Lab office, totaling 25 feet in length, must function as a shear wall based on structural analysis. Consequently, the number and size of openings in this wall must be reduced to avoid structural failure. In the original design, this wall included three openings: one for the door, one for the duct, and one for two pipes. The revised design constraints allow only a single opening, either for the duct or for the two pipes, meaning the door must be relocated.

Architectural constraints: The architect was instructed to note that the mechanical room door could be moved to the West wall and accessed via the West corridor. The new door location must be placed either in one of the corners or in the center of the West wall. Additionally, the architect informed the team that if the contractor chose to route the duct and pipes through the Lab office, a corner soffit would need to be installed. This soffit could embed either one duct or two pipes and must be placed along the East or West wall of the Lab office. The architect expressed a preference for placing both the boilers and the air handling unit on one wall of the mechanical room to preserve the remaining space for storage, aligning with the owner's interests.

Construction constraints: The contractor was instructed to warn the team that due to the vibration sensitivity of the adjacent Lab, no piping or ductwork should be routed through the West corridor. Since pipes are more expensive than ducts, the contractor had to minimize pipe length wherever possible. Due to the limited ceiling height, the duct and pipe could not be installed at different elevations, and no system could be routed above the door. If routing changes were made, both the duct and pipe had to terminate at the same location in the North corridor as in the original design. Only 90-degree bends could be used. The contractor also needed to allow for equipment maintenance space. When all equipment was placed along a single wall, two pieces had to be located in the corners, and one in the middle of the wall.

2.2.2 Scenario B

In Scenario B, another zone of the research facility was presented to the participants, as illustrated in Figure 1.b. Participants were assigned role-specific technical constraints and were instructed to communicate the following constraints to one another during the collaborative session.

Structural constraints: The structural engineer was instructed to inform the team that the Lab on the second floor contained heavy equipment, resulting in a high shear force being applied to the slab underneath. During the design review process, the structural team had identified that the two openings in the Lab floor slab proposed by the contractor, for the pipe and duct risers, would result in structural failure. As a solution, the structural engineer allowed only one opening in the Lab's floor slab, either for one duct or for two pipes. Additionally, the slab below the adjacent Lab office could accommodate a maximum of two openings: one for a duct and one for two pipes. A combined large opening for both duct and pipes was not permitted, as it would lead to structural failure.

Architectural constraints: The architect was instructed to note that the duct and pipes should not be visible in the Lab office, although they could be exposed in the storage room. The architect preferred that any slab openings be placed at the corners of a wall, so the duct and pipes could be concealed within a wall-to-wall cabinet. Although the owner had approved the budget for a cabinet in the Lab office, its final placement had not yet been determined. If the team opted to embed the pipes and duct within the cabinet, they needed to be routed to the corners to preserve the middle section for storage. The architect also preferred that the boilers and air handling unit be placed along a single wall of the mechanical room to allow the remainder of the space to be used for storage, in line with the owner's request.

Construction constraints: The contractor was instructed to inform the team that, due to design constraints, the duct was limited to only one additional bend; otherwise, the air handler would lack sufficient power to serve the Lab. Because the pipe was more expensive than the duct, the contractor was instructed to find the shortest and most efficient route for the pipes, with minimal additions. The ceiling height was low, so the duct and pipe could not be installed at different elevations, and no system could be routed above the door. If routing changes were made, the duct and pipe had to terminate at the same point in the Lab as they did in the original design. Only 90-degree bends were allowed. Finally, the contractor had to consider maintenance space for equipment. When all equipment was located on a single wall, two pieces were to be placed at the corners and one at the center of the wall.

2.2.3 Alternate design options

There were two acceptable solutions to accommodate the structural design changes in Scenario A. In the first solution, all equipment was relocated to the North wall of the mechanical room. The air handling unit was placed in the Northwest corner, with the duct routed through the Lab office via a corner soffit. The boilers were positioned in the middle and the Northeast corner of the North wall. The pipes were routed through the East corridor by creating an opening in the shear wall. In the second solution, all equipment was positioned along the East wall of the mechanical room. The air handling unit was placed in the Southeast corner, with the duct routed through the East corridor by creating an opening in the shear wall. The boilers were positioned in the middle and the Northeast corner of the East wall. The pipes were routed through the Lab office via a corner soffit.

Scenario B also presented two acceptable solutions to accommodate the structural constraints. In both solutions, the pipes were routed from the Northwest corner through the storage room and embedded in the corner of the cabinet in the Lab Office. In the first solution, all equipment was located on the North wall of the mechanical room. The air handling unit was placed in the Northeast corner, with the duct routed through the Lab's floor slab. The boilers were positioned in the middle and the Northwest corner of the North wall. In the second solution, all equipment was located on the West wall of the mechanical room. The air handling unit was placed in the Southwest corner, with the duct routed through the Lab's floor slab. The boilers were positioned in the middle and the Northwest corner of the West wall.

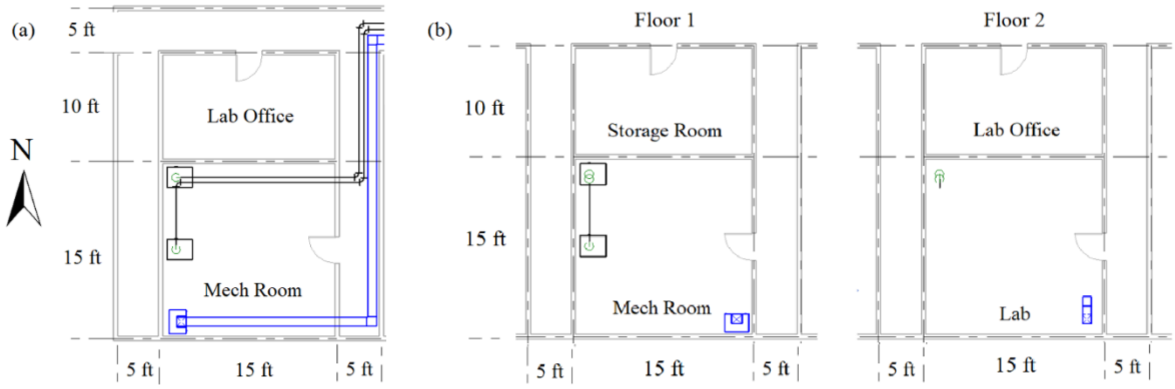

Figure 1: Scenario plans: (a) Scenario A plan; (b) Scenario B plans for floors 1 and 2.

2.3 Digital and physical setup

The 3D models were created using the authoring program, Autodesk Revit. These models included architectural and mechanical. The coordination program, Autodesk Navisworks, was then used to combine both into federated models for use in the experiment. Some visual cues were added to the model to help participants recognize the spaces. These cues include the name of the room written on top of the doors, both inside the room and in the corridor, along with a desk, chair, and planter in the office area, as well as some boxes in the storage area. To reduce the potential for claustrophobia, roofs were set semi-transparent, allowing participants to see the sky. Additionally, doors were hidden, and large windows were incorporated into the corridors to provide light and views of the surrounding trees to reduce perceived enclosure. Figure 2 shows top views of the 3D models for both scenarios. It should be noted that in this figure, the semi-transparent roof was hidden in both models, and the second-floor slab in Scenario B was set to semi-transparent for better visual representation.

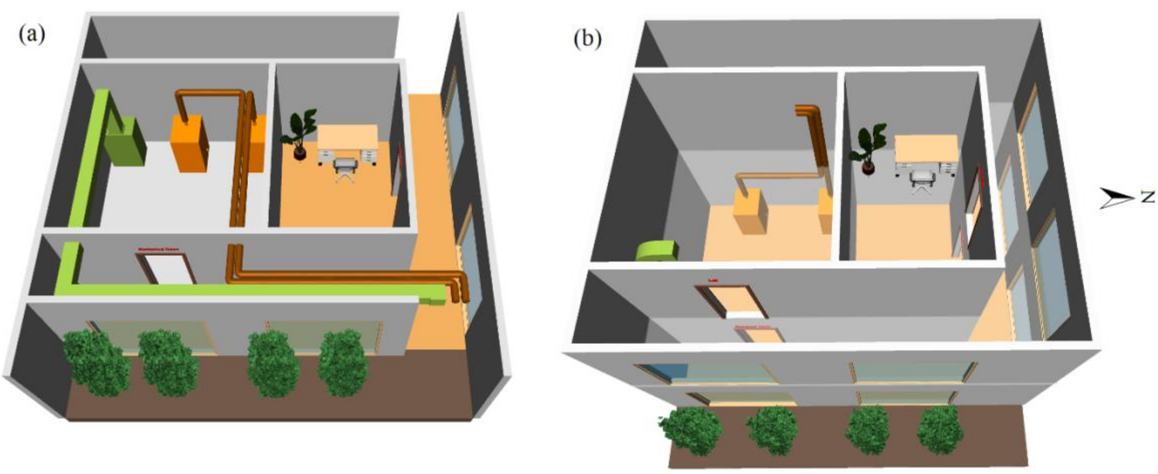

Figure 2: Top views of 3D models: (a) Scenario A, (b) Scenario B.

In the BIM platform, each participant was provided a computer with access to the internet and a headset. They utilized Navisworks to explore the model, and they shared their screens using Zoom, a cloud-based conferencing software for remote online meetings. Participants were asked to turn off their cameras to prevent the impact of facial expressions on team performance, as they were not captured by avatars in VR and have been identified as a factor influencing collaboration efficiency (Astaneh Asl et al., 2023b). Their names were set as their roles for the Zoom profiles. The meeting was recorded with Zoom’s recording feature by an observer from the research team. Participants were seated apart in locations where they could not see or make eye contact with one another and communicated solely via headsets. Participants were only allowed to use the Walk and Look Around navigation mode in Navisworks to replicate the 6DOF navigation in VR. Two viewpoints, 3D snapshots of the model as displayed on the screen, were defined in Navisworks for the first and second floors located in the Southeast corner of the East corridor to allow participants to toggle between two floors in Scenario B. There was only one viewpoint in the same location on the first floor for Scenario A. Participants were allowed to use Navisworks' Markup tool to create annotations on the model, and use Zoom's Annotate tool to create markups for users not sharing their screens. Navisworks allowed users to draw lines, shapes, and arrows as well as add text as markups. Participants were prohibited from using Navisworks' other features, such as visibility tools to hide some parts or make them transparent in the model. The Zoom Annotate tool offered similar features to those in Navisworks, with the added ability to draw freehand and highlight the mouse cursor's location. Through this setup, all participants had access to individual pointer and markup tools, regardless of whether they were actively sharing their screen. It should be noted that markups in Navisworks are created on a static 2D view of the 3D model. If users navigate away from this view after creating a markup, the markup disappears from the screen and can only be seen again by returning to the saved viewpoint generated by the Markup tool. Unlike Navisworks, where markups disappear upon navigating away from the saved viewpoint, Zoom’s annotations remain on the screen regardless of navigation and must be manually erased. Figure 3.a and 3.b show the interface of Navisworks and Zoom annotations tools.

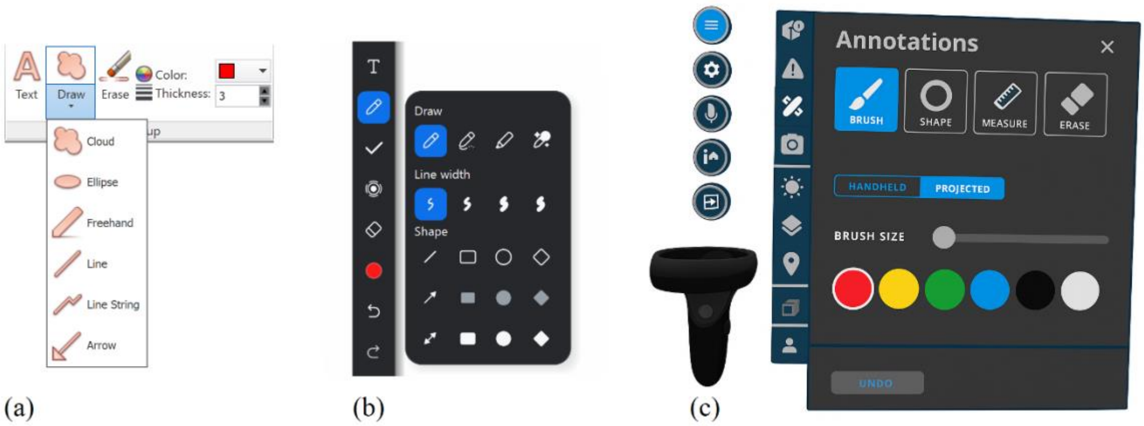

Figure 3: Markup tools: (a) Navisworks' Markup tool, (b) Zoom's Annotate tool, (c) Prospect's Annotations tool.

To hold the meeting in VR, the Prospect by IrisVR program was used. The Prospect plug-in in Navisworks was utilized to export the federated model to the VR environment. The experiment was conducted using the Meta Quest 2 headset. Each participant was allocated a 30 ft by 30 ft physical space, allowing them to explore the virtual model without the need for teleportation, mirroring the navigation experience in the BIM platform. The experiment was conducted in a very large space where participants could not hear each other in the physical space and collaborated solely via VR headset. Avatars were color-coded, and their heights corresponded to the users' physical heights. Participant names were displayed as their assigned roles above the VR avatars’ heads. A microphone symbol next to each name spiked when the user was speaking. To allow participants to access the upper floor in Scenario B, they were instructed to use the fly mode, which elevated the avatar by three feet with each press of a controller button. Pressing the button three times would raise the avatar to the second floor. Participants were equipped with all collaboration tools provided by Prospect, available on a pallet on the left controller for right-handed users. However, participants were only allowed to use the pointer and markup tools; other available features, such as visibility controls, were intentionally disabled as part of the experimental design, consistent with the restrictions applied across both platforms. The pointer tool functioned similarly to a laser pointer. When directed at a surface in the model, the tip would appear as a small sphere matching the user's avatar color at the point of contact. The brush in the Annotations tool enabled users to create 3D annotations in the virtual space using the handheld option, or 2D annotations projected onto surfaces using the projected mode. The only available drawing shape was a circle. Figure 3.c shows the pallet interface with the Annotations tool. The meeting was recorded from the perspective of the observer, who was seen as an avatar in the virtual space by other team members. Figure 4 shows the VR platform interface captured during one of the experiment meetings.

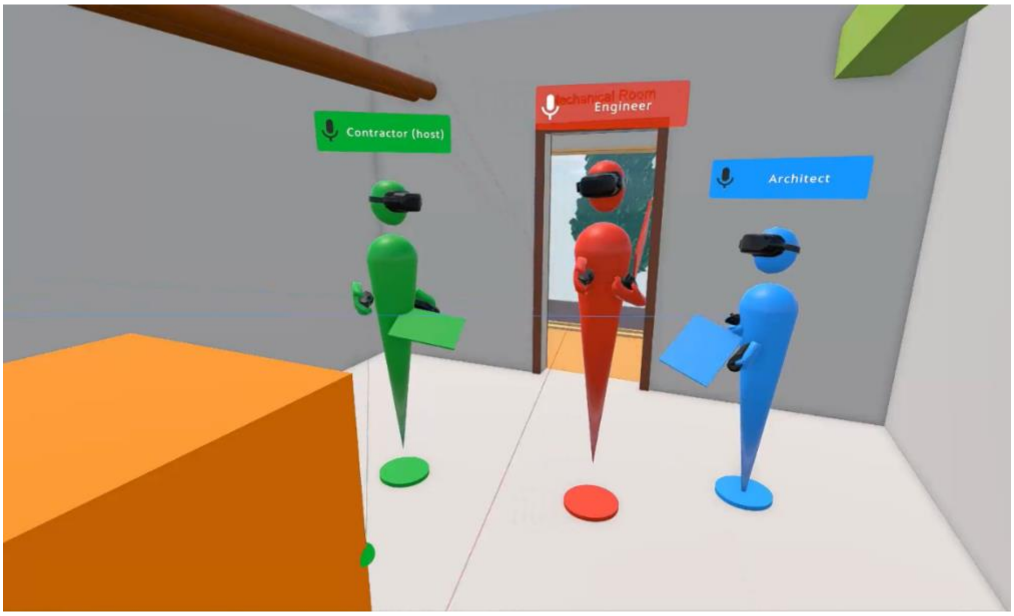

Figure 4: VR platform interface.

2.4 Questionnaires

Three questionnaires of A, B, and C were designed for this experiment. The Questionnaire A contained empty drawings of the facility that only showed the architectural layout on the plan and elevation. The drawings were tailored to each scenario to reflect its distinct layouts. The questionnaire was given to the participants at the end of the meeting. Participants were asked to individually draw the alternative design based on the team's final decision on the drawings. This questionnaire measured whether the individual had the same understanding of the suggested alternate design as other team members.

Questionnaire B was designed to collect participant feedback on their experiences using the BIM and VR platforms for team collaboration. Participants completed platform-specific Questionnaire B following each collaborative session. In the BIM platform questionnaire, participants first indicated whether they were able to recognize speakers, considering that cameras were turned off during the meeting. Four multiple-choice options were provided: (1) “Yes, all the time,” (2) “Yes, most of the time,” (3) “No, only sometimes recognizable,” and (4) “No, it was hard to recognize the speaker.” Participants were also asked about their satisfaction with BIM platform features used to communicate technical requirements and solutions. These satisfaction ratings were collected separately based on whether the participant was actively sharing their screen or viewing a teammate’s shared screen. For these satisfaction ratings, four multiple-choice options were given: (1) “Highly satisfied,” (2) “Satisfied,” (3) “Somewhat satisfied,” and (4) “Not satisfied at all.” Additionally, open-ended questions invited all participants to describe specific BIM features that facilitated or hindered effective communication during collaboration. In the VR platform questionnaire, participants similarly rated their ability to recognize speakers represented by avatars that lacked detailed facial features. The multiple-choice options provided were identical to those used for the BIM questionnaire, ranging from full recognition ("Yes, all the time") to difficulty recognizing speakers ("No, it was hard to recognize the speaker"). Participants also rated their satisfaction with VR platform features for communicating technical constraints and solutions, using the same four-point satisfaction scale as in the BIM questionnaire. Finally, open-ended responses allowed participants to identify and discuss the VR platform features that either supported or presented barriers to team communication.

Questionnaire C was distributed at the end of the experiment, asking participants to compare the efficiency of their team collaboration using BIM and VR platforms and state their platform preference across four categories of (1) spatial understanding and awareness, (2) team communication, (3) use of visual communication tools, and (4) technical understanding. In the spatial understanding and awareness category, participants evaluated their ability to: (a) navigate the model, (b) understand the design, and (c) be aware of their location in the model. In the team communication category, participants reported their preferences for: (a) collaborating actively with teammates, and (b) recognizing team members when they spoke. In the visual communication tools category, participants assessed: (a) the effectiveness of the pointer tool, (b) the effectiveness of the markup tool, (c) their ability to point out building components, (d) follow a team member's pointer, (e) draw or mark up their ideas, and (f) understand the markups made by others. In the technical understanding category, participants reflected on how well each platform supported their ability to: (a) explain their technical constraints, (b) suggest alternative design options, (c) understand their teammates' technical constraints, and (d) follow resolution suggestions made by others. Table 2 summarizes all data collection tools used in the paper and their role in evaluating collaboration efficiency, effectiveness, and participant experience.

Table 2: Evaluation framework.

Data collection tool	Assessment basis	Data form	Aspect evaluated
Meeting recordings	Objective	Quantitative	Collaboration efficiency by measuring meeting duration
		Qualitative	Interaction with model and teammates through observation
Questionnaire A	Objective	Quantitative	Collaboration effectiveness by assessing individual report of team decision
Questionnaire B	Subjective	Quantitative, Qualitative	User experience with each platform through structured survey
Questionnaire C	Subjective	Quantitative	Platform comparison through structured survey

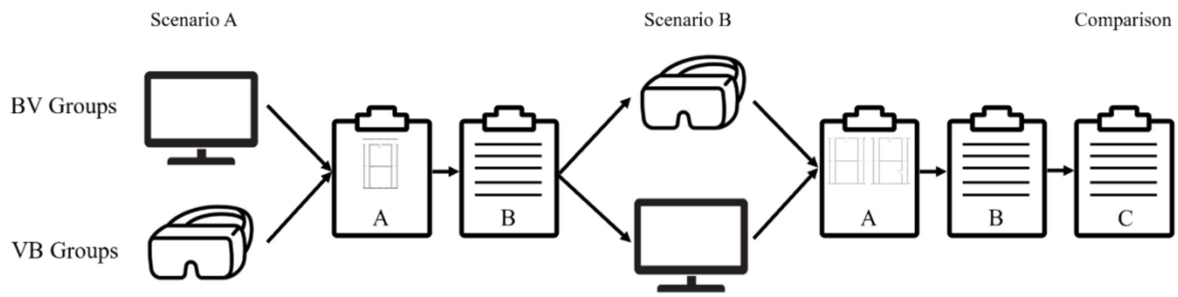

Figure 5: Experiment procedure.

2.5 Procedure

Groups were named according to the order in which they used the platforms: groups labeled 'BV' began with BIM, whereas 'VB' groups initiated collaboration in the VR environment. At the start of the experiment, each participant was given role-specific technical information and detailed instructions on the procedure. They were then allotted time prior to their meeting to review the technical information and explore the model individually, in either the BIM or VR platform, based on group assignment, to gain a clear understanding of the task and model. The meeting was divided into three phases. In the first phase, participants were instructed to share all role-specific technical constraints, without discussing alternative design solutions. To support accurate and complete information sharing, each participant was provided with a small bullet-point cheat sheet, a shortened version of their full role-specific description, summarizing their assigned constraints in case they did not remember them. In the second phase, the observer read a text summarizing all the constraints to recap what the team shared in the first phase. In the last phase, teams collaborated to find an alternate design accommodating the structural design change. Groups started with Scenario A, and then switched the platforms and worked on Scenario B. Questionnaires A and B were distributed after each meeting, where participants drew the team's decision on the drawings in Questionnaire A and reflected on their experience in the platform they collaborated in by filling out Questionnaire B. At the end of the experiment, Questionnaire C was distributed to capture the participants' reflections on their experiences in both platforms and their comparison. Figure 5 shows the experiment procedure. Prior to the experiment, participants were provided with health and safety guidelines from the VR headset manufacturer, Meta. They were informed that immersive VR sessions would not be allowed to exceed 30 minutes in accordance with these guidelines and were instructed to immediately remove the headset if they experienced discomfort or dizziness at any point during the session.

3. RESULTS

The results of the experiment are presented in four sections of 3.1 Meeting Duration, 3.2 Team Decision Report, 3.3 Platform Features, and 3.4 Platform Preference.

3.1 Meeting duration

The first criterion considered in data analysis was the duration of the meeting spent in BIM and VR platforms to find the alternate design. The meeting duration was calculated from the moment a team member started exchanging the first technical information until the team finalized an alternative design, with all members confirming a clear understanding of the decision. The time spent by the observer reading the summary text during the second phase was excluded from the meeting duration. The observer also had minimal interruptions during the meeting to remind the participants of the rules that were omitted from the meeting duration calculations. Some teams spent a considerable amount of time in the first phase understanding the technical constraints and mentally exploring potential solutions, whereas others opted to briefly exchange technical information and dedicated more time to discussing the alternative design in the third phase. The latter group often needed to ask their teammates to re-explain the constraints in the third phase as they rushed through the first phase. Consequently, the research team determined the total meeting duration as the primary comparison criterion without considering the time spent for information exchange and team discussion separately. For data analysis, meeting durations were converted to seconds; however, for ease of interpretation, they are presented in minutes and seconds in the tables. Table 3 presents the meeting duration for all groups, and Figure 6 shows it graphically with bar charts.

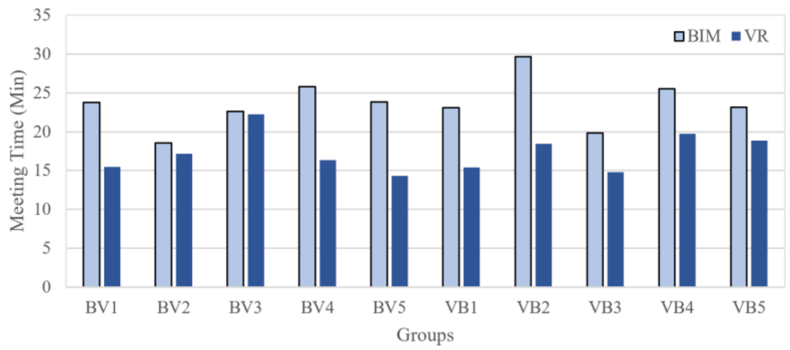

Figure 6: Meeting time spent by groups in BIM and VR platforms.

Table 3: Meeting duration for all groups (Min:Sec).

BV Groups	Scenario A BIM	Scenario B VR	VB Groups	Scenario A VR	Scenario B BIM
BV1	23:46	15:26	VB1	15:22	23:05
BV2	18:31	17:09	VB2	18:28	29:40
BV3	22:35	22:14	VB3	14:48	19:49
BV4	25:48	16:19	VB4	19:45	25:31
BV5	23:52	14:20	VB5	18:52	23:09

All teams spent less time in the VR platform to reach an alternative design compared to BIM. The difference between the meeting durations spent in the two platforms was relatively low for groups BV2 and BV3 compared to other teams. Observations indicated that team BV2 identified the first acceptable alternative design within 11 minutes and 45 seconds; however, the team chose to continue the discussion and ultimately reported the second acceptable solution as their final decision. The architect in team BV3 experienced technical difficulties during the meeting. Initially inaudible, he was eventually disconnected due to a weak internet connection, which left him out of the discussion between the structural engineer and the contractor. Upon rejoining, the architect discovered that the other two team members had overlooked his constraint of placing all equipment on a single wall to preserve space for storage. As a result, the team realized they had been discussing an incorrect solution. Although teams BV2 and BV3 spent a relatively similar amount of time in both platforms, observations suggest that their meetings could have concluded earlier in the VR environment.

Before selecting an appropriate statistical test, the Shapiro-Wilk test was conducted to determine whether the meeting duration datasets were normally distributed. The null hypothesis of this test states that the data are normally distributed, while the alternative hypothesis suggests a deviation from normality. A p-value less than the significance value of 0.05 indicates that the null hypothesis can be rejected, implying that the data are not normally distributed. Table 4 presents the p-values from the Shapiro-Wilk test used to assess the normality of the meeting duration in BIM and VR platforms.

Table 4: Shapiro-Wilk test results for meeting durations.

Groups	p-value (BIM)	p-value (VR)
BV Groups	0.42121	0.22149
VB Groups	0.78830	0.25885
Total	0.71840	0.47307

Since all p-values from the Shapiro-Wilk test exceeded the significance level of 0.05, the meeting duration datasets were considered normally distributed. Based on these results, the paired t-test was selected as an appropriate method for statistical comparison. All analyses were conducted using two-tailed tests to allow for the detection of differences in either direction, without assuming a specific outcome in advance. This approach ensured consistency across comparisons of meeting durations between platforms and participant groups. Table 5 presents the results of two-tailed paired t-tests comparing the mean meeting durations between the BIM and VR platforms for BV and VB groups, as well as the combined dataset. In all cases, the mean meeting duration was shorter when using VR compared to the BIM platform. To assess statistical significance, p-values were compared against the significance level of 0.05. For BV groups, the reduction in meeting time from 22 minutes and 54 seconds in BIM to 17 minutes and 6 seconds in VR was statistically significant. For VB groups, the drop from 24 minutes and 15 seconds to 17 minutes and 27 seconds was more substantial and highly significant. When aggregating all groups, the average meeting duration decreased from 23 minutes and 35 seconds in the BIM platform to 17 minutes and 16 seconds in VR, with a highly significant result. These findings suggest that the VR platform led to significantly shorter meetings compared to BIM, indicating potential efficiency benefits in team collaboration workflows.

Table 5: Two-tailed paired t-test results for meeting durations.

Groups	Mean Duration in BIM (Min: Sec)	Mean Duration in VR (Min: Sec)	p-value
BV Groups	22:54	17:06	0.04645
VB Groups	24:15	17:27	0.00540
Total	23:35	17:16	0.00036

To further illustrate the efficiency of using the VR platform, the ratio of average meeting durations (VR/BIM) and the corresponding time savings were calculated. These values, based on the mean durations, are presented in Table 6. For BV groups, the average VR meeting duration was 74.6% of the BIM platform duration, resulting in a 25.4% time savings. VB groups showed a similar pattern, with VR meetings lasting only 72.0% as long as BIM platform meetings, equating to a 28.0% time savings. Across all groups, the overall average VR meeting duration was 73.3% of the BIM platform average, indicating a 26.7% reduction in meeting time. These consistent reductions in meeting time across all groups suggest that immersive VR environments may offer significant efficiency advantages over traditional BIM platforms in remote multidisciplinary team collaboration.

Table 6: Meeting duration ratio (VR/BIM) and time savings (%).

Groups	Meeting Duration Ratio (VR/BIM)	Time Savings
BV Groups	74.6%	25.4%
VB Groups	72.0%	28.0%
Total	73.3%	26.7%

3.2 Team decision report

This section presents the results of the data analysis based on Questionnaire A. Each team member's drawing of the team's alternate design decision was evaluated based on the accuracy of four elements: the locations of the boilers and air handling unit, and the routing of the duct and pipes. A maximum of four points could be awarded, with one point assigned for each accurately reported element. For routing, scoring focused on whether participants selected the correct location for penetrations, such as the appropriate wall, slab, corridor, corner soffit, cabinet, etc., regardless of the exact placement of the duct and pipe in the mechanical room. For example, if a boiler was placed incorrectly but its associated route passed through the correct corridor in Scenario A, the routing was still considered accurate. Table 7 summarizes the individual member scores, where A stands for the Architect, E stands for the Engineer, and C stands for the contractor. Figure 7 presents the overall team scores, calculated by summing the individual scores of each team member. The results showed that teams either achieved equal total scores in both platforms or had higher scores in the VR platform.

Table 7: Team member scores based on the accuracy of the reported team decision.

BV Groups	Member	Score		VB Groups	Member	Score	
		BIM	VR			BIM	VR
BV1	A	4	4	VB1	A	4	4
	E	4	4		E	4	4
	C	4	4		C	4	4
BV2	A	4	4	VB2	A	4	3
	E	2	4		E	3	4
	C	2	3		C	4	4
BV3	A	2	4	VB3	A	0	3
	E	3	4		E	4	4
	C	4	4		C	3	3
BV4	A	4	4	VB4	A	4	4
	E	4	4		E	4	4
	C	0	2		C	3	4
BV5	A	4	4	VB5	A	4	4
	E	0	4		E	4	4
	C	0	4		C	4	4

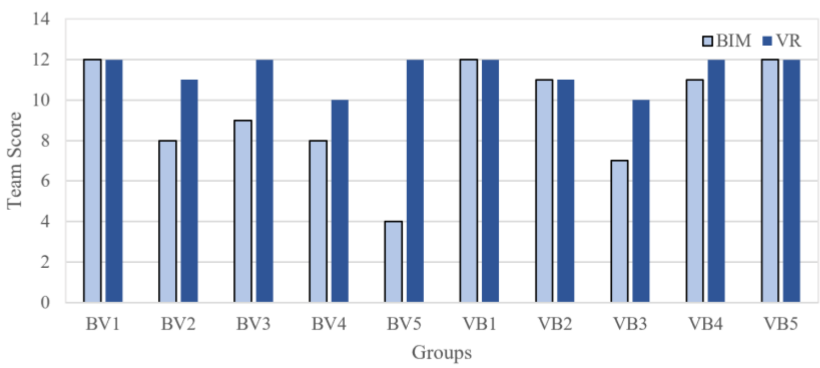

Figure 7: Team scores based on the accuracy of the reported team decision.

Furthermore, Table 8 presents the number of teams in which all members accurately reported the final team decision, along with the total number of individual members who correctly reported the decision, in both the BIM and VR platforms. Across both BV and VB groups, a greater number of teams achieved complete reporting accuracy in the VR platform compared to BIM. Three teams in each group successfully reported the final decision with full member agreement in VR, totaling six teams. In contrast, only one team in the BV group and two teams in the VB group achieved full accuracy in the BIM platform, totaling three teams. The total number of accurate individual reports was also higher in the VR condition, with 25 members, compared to 19 members in BIM. While these results suggest a performance advantage for VR, a deeper understanding of how teams arrived at their decisions and the specific factors influencing accuracy required further examination. The following section of 3.2.1, Qualitative Observations on Team Performance and Decision Reporting, provides a qualitative analysis of team collaboration, followed by the section 3.2.2, Quantitative Analysis of Team Decision Reporting, that presents a quantitative statistical comparison of individual reporting accuracy across platforms.

Table 8: Number of teams with all members accurately reporting the final team decision, and number of members with accurate individual reports.

Groups	BIM		VR	
	Team	Members	Team	Members
BV Groups	1	8	3	13
VB Groups	2	11	3	12
Total	3	19	6	25

3.2.1 Qualitative observations on team performance and decision reporting

Observations showed that teams and individuals used different methods to exchange technical constraints and suggest solutions for the alternate design. Some meetings did not include any use of markups and were solely dependent on the use of the mouse cursor in the BIM platform and the pointer in the VR environment for collaboration. In the rest of the meetings, markups were utilized in different ways. Figure 8 illustrates some examples of the markups created during meetings. In the VR platform, individuals were mostly reluctant to draw 3D markups in the 3D space using the handheld mode and mainly created markups on the surfaces. Using the shape markup, some teams specified the locations of equipment and openings as shown in Figure 8.a. Since typing was not a tool available in VR, they used the brush tool to draw the letters on the surface as demonstrated in Figure 8.a. Some teams also used this tool to draw the equipment and routes of pipes and duct as depicted in Figure 8.b. Teams also took advantage of different markup colors to color-code their drawings, which matched the colors of the mechanical and piping systems for recognition, as seen in Figure 8.b. In the BIM platform, teams mostly used Navisworks lines and shapes features for markup. As illustrated in Figure 8.c., lines were used to draw the location of the equipment in a perspective view. Those individuals who were not sharing the screen used Zoom's Annotate tool to draw markup on the shared screen, as presented in Figure 8.d. They preferred its freehand drawing tool for markup.

Teams were also observed in terms of how they used avatar body language to communicate during meetings in VR. Since the headset location was mapped to the avatar's head, participants could perceive where teammates were looking and often turned to face one another during conversations. Gestures such as head nods were used to indicate agreement, and hand movements were employed to point toward equipment or spatial directions, even without the use of a pointer tool. In some cases, participants waved to draw the attention of teammates who were exploring a different area of the model and to guide them toward the space where the team conversation was taking place. Additional body language cues, such as head scratching or momentarily remaining still while considering design options, were observed during team interactions. While not always explicitly communicative, these subtle behaviors offered insight into participants' cognitive states, such as focused thinking, temporary uncertainty, or silent decision-making. Collectively, these avatar-based gestures appeared to enhance participants' sense of presence and may have supported nonverbal aspects of collaboration.

Members in groups BV1, VB1, and VB5 collaboratively worked together in both the BIM and VR platforms and accurately reported the final team decision. In groups BV3, BV5, and VB4, members reported the team decision correctly in VR, while some made mistakes in the BIM platform. In the remaining groups, mistakes were made in both platforms. The following observations across all teams provide additional insight into the factors that may have contributed to inaccurate reporting. Each team exhibited different dynamics and communication styles, which influenced how information was shared and how final decisions were individually reported. These observations describe what was visibly observed during the meetings and do not imply access to participants' internal reasoning. Because the observed situations were specific to each team's interactions and skill sets, they are presented at the team level rather than grouped into generalized categories. A synthesized interpretation of how these observations inform effective collaboration practices is provided at the end of this section.

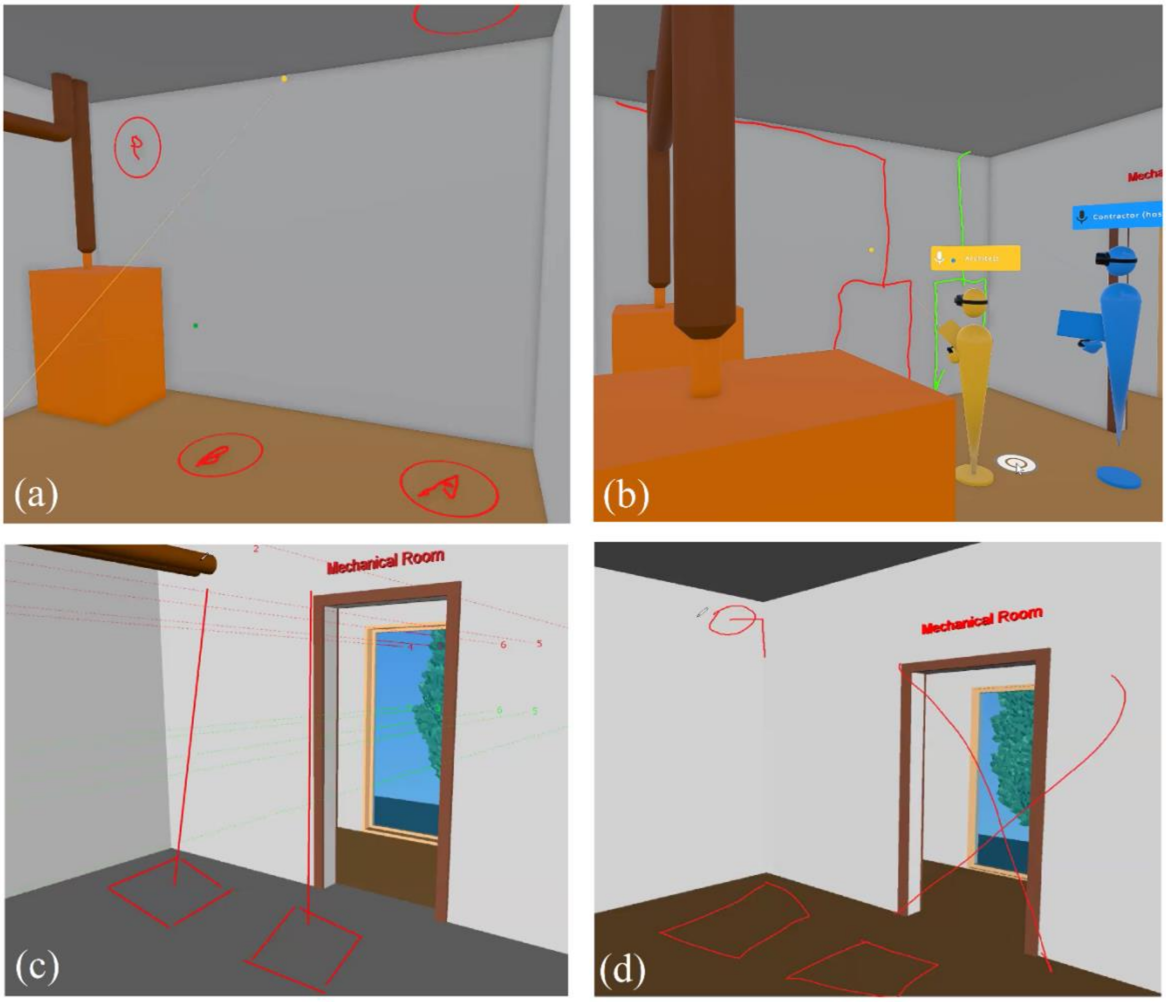

Figure 8: Examples of markup use for communication: (a) shape markup in VR platform, (b) brush markup in VR platform, (c) Navisworks' line markup in BIM platform, (c) Zoom's freehand draw markup in BIM platform.

In the BIM session for Group BV3, the meeting was led by the Contractor, who explained the proposed solution to the team and reported the final decision correctly. He clearly demonstrated the locations of the boilers and air handling unit, as well as the routing for ducts and pipes. However, it was observed that during the explanation, he moved continuously through the space and frequently turned around in the mechanical room. This may have disoriented the Engineer and the Architect, making it harder for them to fully grasp the final team decision. Additionally, the markup tool was not utilized; instead, the mouse cursor was used to point out elements in the model and show routings. This may have contributed to difficulties in maintaining a shared understanding of the final team decision. During the BIM session for Group BV5, the solution was explained verbally to the team members without the use of a mouse or any visual aid to indicate the locations of equipment or routing paths. The explanation also lacked spatial references such as directions (e.g., North or East), which further limited clarity. While team members appeared to assume they were on the same page, their individual reports of the final decision revealed discrepancies. This suggested that the verbal explanation alone was insufficient to establish a shared spatial understanding of the solution. In the BIM session for Group VB4, the Contractor reported the location of the air handling unit incorrectly in the individual decision report. The Architect shared the screen and used the mouse cursor to explain the solution, both on the first and second floors. During the discussion, the Contractor asked for the reasoning behind relocating the air handling unit. In response, the Engineer provided the necessary technical justification. The Contractor then sought clarification, as he was under the impression that the pipes were routed through the corridor. The Architect explained the pipe routing using the model and mouse cursor to ensure clarity. However, at the conclusion of the meeting, the Architect simply stated that the duct would be routed directly through the slab from the mechanical room, assuming all members still recalled the previously discussed location of the air handler. This lack of explicit visual confirmation or verbal reinforcement of the complete solution likely contributed to the inaccurate report.

Among the remaining four teams, Group BV4 was the only team in which only one member made mistakes in both platforms, while the other two members reported the decision correctly. In Groups BV2, VB2, and VB3, only one team member reported the final decision correctly in both platforms. In the BIM session for Group BV4, the Architect and Engineer actively discussed the solution and finalized it. The mouse cursor was used to indicate the locations of equipment and routing paths during their discussion. Before concluding, the Contractor asked the team to recap the solution once more, and the Architect and Engineer provided a clear summary using the model. However, the Contractor appeared to be confused about spatial orientation, having earlier asked the team which direction they were facing in the model. In his individual report, he placed all the equipment on the wrong wall and routed the duct and pipes differently from the team's agreed-upon solution. In the VR session for Group BV4, the Engineer visually marked the locations of equipment and openings in the lab using a circle markup and annotated them with initials to help the team understand the solution as seen in Figure 8.a. 'A' indicated the air handling unit, 'B' the boiler, 'P' the pipe opening, and 'D' the duct opening. At the end of the meeting, the Contractor asked for a recap and repeated the solution back to the team using his pointer to confirm his understanding, which the team validated. While the Contractor's report accurately reflected the locations of the equipment, the routing of pipes and duct was incorrect. This was likely due to the participant's limited skill in representing routing paths in plan and elevation views in a two-story building. Although observations indicated that he understood the solution conceptually, only 2 out of 4 points were assigned to his report of the team decision. However, the Contractor demonstrated notable improvement in the VR session by actively seeking clarification and accurately reporting the equipment locations while showing he understood the team's decision conceptually in the VR platform.

In the BIM session for Group BV2, the solution was found by the Architect, who also delivered the recap of the solution by using the mouse cursor to indicate the locations of equipment and routing paths. During the recap, the Contractor was involved in the conversation. The Architect also asked the Engineer to confirm agreement with the proposed solution, which he did. The Architect was the only member who reported the solution correctly. The Contractor specified the location of the boilers and pipe routes correctly but did not include the location of the air handling unit or the duct in her report. Notably, there were signs of erased drawings on her submission, suggesting that she was either unsure of the solution or did not fully remember the agreed-upon configuration. The Engineer placed all equipment on two incorrect walls, although the routing paths were represented correctly. In the VR session for Group BV2, the Engineer actively led the effort to find the solution and subsequently brought the Architect into alignment with the proposed design. The Engineer used the freehand markup tool to draw the locations of the equipment on the floor and indicate the openings on the wall. The Architect provided a recap of the solution to ensure the Contractor was following. The Contractor appeared confused about the piping route, despite the Architect providing a clear explanation of how it would pass through different spaces in the building; however, no clarifying questions were asked by the Contractor. The Architect and Engineer both reported the solution correctly, while the Contractor made an error in reporting the piping route.

In the BIM session for Group VB2, the Engineer shared the screen throughout the meeting while the Architect and the Contractor collaboratively found the solution. They verbally guided the Engineer through the model to explain the proposed configuration. The discussion was conducted primarily through verbal exchanges while all team members viewed the model. This approach contributed to the Engineer's incorrect report of the duct route, as the verbal guidance alone was insufficient to fully clarify the routing path. In the VR session for Group VB2, the Engineer and the Contractor collaboratively found the solution while positioned inside the mechanical room. The Architect followed their conversation from the East corridor, observing the discussion through the doorway. The Contractor showed the piping opening location at the Northeast corner of the room using his pointer, an area that was outside the Architect's line of sight. This most likely contributed to the Architect's incorrect report of the piping route, as he assumed the opening was located on the East wall rather than the North wall in that corner.

In the BIM session for Group VB3, the Engineer found the solution, and the team asked him to share his screen to explain it. While describing the proposed design, he continuously turned around within the mechanical room, which likely disoriented the Architect. As a result, the Architect reported the locations of all equipment on the wrong wall with incorrect routing. The Contractor also reported the piping route incorrectly, despite the Engineer having provided a clear explanation of the routing path using the mouse cursor. In the VR session for Group VB3, the Engineer found the solution and guided the other team members through it. While explaining the piping routes, he stated that the pipes would exit to the North, but his pointer was directed toward the East wall, as he was facing East at the time. Additionally, his hand and pointer were moving while he was speaking, which likely led the Architect and the Contractor to interpret the pointer's movement as indicating the intended opening location, contributing to their similar incorrect reports of the piping route through the East wall.

Overall, the qualitative observations revealed that teams used a range of strategies to communicate technical constraints and collaboratively arrive at design solutions. Across both platforms, teams that visually reinforced their proposals tended to demonstrate stronger alignment in individual reporting. In contrast, unclear spatial references, lack of visual confirmation, and assumptions about shared understanding often contributed to reporting errors. These findings suggest that while collaboration outcomes depended on how teams used available tools, the VR platform enabled a more visually communicative environment for clarifying misunderstandings and reinforcing shared spatial understanding during the decision-making process. Although VR allowed teammates to move freely, this freedom occasionally led to misalignment when participants were not spatially positioned to see or follow what others were referencing. In one instance, a participant observed the discussion from outside the mechanical room, resulting in a misunderstanding about the location of a proposed pipe opening. These findings suggest that while VR supports communication, its effectiveness depends on how actively team members manage spatial orientation and ensure mutual visibility during collaboration.

3.2.2 Quantitative analysis of team decision reporting

The following quantitative analysis complements the observations by comparing team member scores across platforms and evaluating the statistical significance of differences in reporting accuracy. To assess the normality of team member scores, Shapiro-Wilk tests were conducted. The results are presented across BV groups, VB groups, and the combined dataset for both the BIM and VR platforms in Table 9. In all cases, the p-values were well below the significance threshold of 0.05, indicating that the score distributions significantly deviate from normality. Given these results, the non-parametric two-tailed Wilcoxon Signed-Rank test was deemed appropriate for further analysis of team member scores. Table 10 presents the results of this test, which was used to compare scores between the BIM and VR platforms across BV groups, VB groups, and the combined dataset.

Table 9: Shapiro-Wilk test results for team member scores.

Groups	p-value (BIM)	p-value (VR)
BV Groups	0.0007888235	0.0000008629
VB Groups	0.0000040971	0.0000034810
Total	0.0000003172	0.0000000027

Table 10: Two-tailed Wilcoxon Signed-Rank test results for team member scores.

Groups	Mean Score in BIM	Mean Score in VR	p-value
BV Groups	2.7	3.8	0.01675
VB Groups	3.5	3.8	0.25684
Total	3.1	3.8	0.00692

The p-values from the two-tailed Wilcoxon Signed-Rank tests were compared against a significance threshold of 0.05 to determine whether the observed differences were statistically significant. In the BV groups, the average team member score increased from 2.7 in the BIM platform to 3.8 in the VR platform, representing a statistically significant improvement. In the VB groups, scores also rose from 3.5 in the BIM platform to 3.8 in VR; however, this difference was not statistically significant. While both BV and VB groups showed relatively similar performance in the VR platform, members of the VB groups demonstrated stronger performance in the BIM platform compared to the BV groups, resulting in a smaller difference between BIM and VR outcomes. These differences in team interaction patterns are further contextualized by the observational analysis discussed in Section 3.2.1, Qualitative Observations on Team Performance and Decision Reporting. When combining all groups, the average score improved from 3.1 in the BIM platform to 3.8 in VR, indicating a statistically significant overall improvement. These results suggest that participants were generally more successful in accurately reporting the final team decision when using the VR platform.

3.3 Platform features

This section presents the results of the data analysis based on Questionnaire B, in which participants reflected on their experience with each platform. The results are discussed separately for each BIM and VR platform.

3.3.1 BIM platform features

To evaluate the effectiveness of the BIM platform in supporting team collaboration during team meetings, participants were asked follow-up questions regarding their ability to recognize speakers without the use of a camera in the video call, as well as their satisfaction with the platform's features for communicating technical requirements and proposing alternative design solutions. Responses were collected separately based on whether the participant was sharing their screen or viewing a teammate's screen. Responses to the question about speaker recognition are summarized in Table 11. Most participants reported a clear ability to recognize who was speaking, despite the absence of video. A total of 93.3% indicated they were able to recognize speakers all the time, while the remaining 6.7% reported doing so most of the time. These results suggest that audio cues and team familiarity were sufficient to support effective verbal communication in the BIM platform without the use of cameras.

Table 11: Participant responses on recognizing speakers without the use of cameras (%).

Groups	All the time	Most of the time	Some times	Hard to recognize
BV Groups	100.0%	0.0%	0.0%	0.0%
VB Groups	86.6%	13.3.%	0.0%	0.0%
Total	93.3%	6.7%	0.0%	0.0%

Satisfaction with the platform's features when participants were sharing their screens is shown in Table 12. In the BV groups, only one participant did not share the screen, while in the VB groups, four participants opted not to share. The percentages reported in Table 12 are based on the responses of those who actively shared their screens during the meeting. Participants generally reported positive experiences when using the BIM platform to share their screen during meetings. Across all responses, most participants expressed a positive experience, with 65.9% reporting they were highly satisfied and 26.0% satisfied. A smaller portion, 8.1%, were somewhat satisfied, and no participants expressed dissatisfaction. These results suggest that the screen-sharing feature in BIM was perceived as effective for communicating technical requirements and proposing design solutions during collaborative sessions. Satisfaction remained high when participants viewed a teammate's screen instead of sharing their own, as summarized in Table 13. Most participants expressed a positive experience, with 76.8% reporting they were highly satisfied and 13.3% satisfied. A smaller share, 6.7%, were somewhat satisfied, while only 3.4% were not satisfied. These findings indicate that BIM's screen-sharing feature was also effective in supporting understanding and engagement during collaborative decision-making, even when participants were in a more passive viewing role. When participants were sharing their own screen in the BIM platform, responses differed between the BV and VB groups. In the BV group, 50.0% of participants reported being highly satisfied and 42.9% were satisfied. In the VB group, 81.8% were highly satisfied and 9.1% were satisfied. In contrast, when participants were viewing a teammate's screen, responses were more similar across the two groups. In the BV group, 73.6% reported being highly satisfied and 13.3% were satisfied, while in the VB group, 80.0% were highly satisfied and 13.3% were satisfied. The remaining participants in both conditions reported being somewhat satisfied or not satisfied, with relatively similar proportions across groups. It should be noted that in the VB groups, four participants chose not to share their screen, while nearly all participants in the BV groups did. This difference in participation may have influenced the distribution of satisfaction responses.

Table 12: Participant satisfaction with BIM platform features for communicating technical requirements and suggesting solutions when the participant shared the screen (%).

Groups	Highly satisfied	Satisfied	Somewhat satisfied	Not satisfied
BV Groups	50.0%	42.9%	7.1%	0.0%
VB Groups	81.8%	9.1%	9.1%	0.0%
Total	65.9%	26.0%	8.1%	0.0%

Table 13: Participant satisfaction with BIM platform features for communicating technical requirements and suggesting solutions when teammates shared the screen (%).

Groups	Highly satisfied	Satisfied	Somewhat satisfied	Not satisfied
BV Groups	73.6%	13.3%	13.3%	0.0%
VB Groups	80.0%	13.3%	0.0%	6.7%
Total	76.7%	13.3%	6.7%	3.3%

Analysis of the written responses in Questionnaire B revealed that participants identified screen sharing and markup tool as useful features for supporting team collaboration in the BIM platform. Some examples of the participant comments are presented in Table 14. Some participants who shared their screen indicated that this feature was valuable for aligning the team's understanding by allowing everyone to view the model from their perspective. Conversely, some participants who followed the shared screen noted that it helped them clearly see the presenter's view of the model and better understand the technical constraints or solutions being discussed. Some also found the markup tool useful for explaining technical constraints and discussing alternative design options.

Table 14: Participant comment examples for supportive BIM platform features for team collaboration.

Feature	Comment
Screen Sharing	I liked explaining my solution by sharing the screen, which was my viewpoint.
	When team members shared their location and explained the problem, it helped me understand where the problem was, and was able to find the solution.
Markup Tool	The markup helped to mark positions of the duct and pipes and the units.
	Markups helped to discuss and come to a solution quickly.

Table 15: Participant comment examples for challenging BIM platform features for team collaboration.

Feature	Comment
Screen Sharing	The screen share was a double-edged sword in that it also created challenges in collaboration. Say if one person had the solution available, they needed to wait until they could share their screen.
	Only one person can suggest ideas at one time by screen sharing. Having to wait for someone to share the screen was inefficient.
Markup Tool	Annotating certain elements was hard.
	When we marked up at one spot and then looked around, the markup was shifted.

Participants found the same screen sharing and markup tool as features that caused challenges in team collaboration. Some examples of the participant comments are presented in Table 15. Several participants noted that having to wait their turn to share the screen limited spontaneous idea sharing. Others pointed out that Navisworks markups would disappear and Zoom markups would shift when the view was changed, making it difficult to maintain visual continuity during communication. Some also found it challenging to markup some elements on the screen. Observations showed that some individuals faced challenges in showing 3D elements on the 2D screen with markups to convey their thoughts.

Overall, participants found the screen sharing and markup tools in the BIM platform helpful for communicating technical information; however, limitations in simultaneous interaction and the visual continuity of markups occasionally hindered team coordination. These mixed experiences highlight both the strengths and constraints of using traditional BIM tools for remote collaboration.

3.3.2 VR platform features

To evaluate the effectiveness of the VR platform in supporting team collaboration, participants were asked follow-up questions regarding their ability to recognize speakers represented as avatars and their satisfaction with the platform's features for communicating technical requirements and proposing alternative design solutions. Participant responses to the speaker recognition question are summarized in Table 16. Most participants reported being able to recognize speakers consistently while interacting through VR avatars. A total of 63.3% of participants indicated they were able to recognize speakers all the time, while 33.3% reported doing so most of the time. Only 3.3% indicated they were able to recognize speakers only sometimes, and none reported difficulty recognizing who was speaking. Compared to the BIM platform, speaker recognition was lower in the VR environment. Participants' written feedback and observational data offered possible explanations for this difference, as discussed later in this section.

Table 16: Participant responses on recognizing speakers with VR avatars (%).

Groups	All the time	Most of the time	Some times	Hard to recognize
BV Groups	73.3%	20.0%	6.7%	0.0%
VB Groups	53.3%	46.7%	0.0%	0.0%
Total	63.3%	33.3%	3.3%	0.0%

Satisfaction with the VR platform's features for communicating technical information and design solutions is summarized in Table 17. Most participants expressed a positive experience, with 76.6% reporting they were highly satisfied and 23.3% satisfied. No participants reported being somewhat satisfied or dissatisfied. Compared to the BIM platform, where 65.9% of participants were highly satisfied and 26.0% satisfied when sharing their screen, satisfaction levels were slightly higher in the VR environment. These results indicate that both platforms were positively received for supporting team communication and collaborative problem-solving.

Table 17: Participant satisfaction with VR platform features for communicating technical requirements and suggesting solutions (%).

Groups	Highly satisfied	Satisfied	Somewhat satisfied	Not satisfied
BV Groups	93.3%	6.7%	0.0%	0.0%
VB Groups	60.0%	40.0%	0.0%	0.0%
Total	76.6%	23.3%	0.0%	0.0%

Participants found voice quality, avatar and markup tool as challenging features for team collaboration in VR platform. Some examples of the participant comments are presented in Table 19. A considerable number of participants expressed challenges in communication due to the quality of voice. It should be noted that the audio quality in the VR environment, as heard through the VR headset, was lower compared to the audio quality experienced during Zoom meetings using the over-ear headset. An echo effect was also observed, resulting from the VR headset capturing and playing back the participants' voices through its built-in microphone and speakers. This audio feedback loop created a noticeable reverberation during communication. The research team was aware of this issue and minimized its effect by lowering the audio level on the VR headsets, but this did not completely resolve the problem, as some participants would increase the audio level to hear their teammates better. Participants also expressed difficulty locating their teammates within the virtual space. Observations confirmed that team members often had to verbally share the name of the room they were in to help others find them. This challenge was primarily due to the lack of directional audio, which made it difficult to determine the location of a speaker based on sound alone. Some participants also reported difficulty identifying who was speaking, even though a microphone icon next to the avatar's name became active during speech. Additionally, the echo effect occasionally triggered small spikes in the microphone indicators of all team members, making it harder to distinguish the actual speaker. This suggests that visual indicators alone, without directional audio or facial expressions, were not always sufficient for reliable speaker recognition. The reported challenges helped contextualize the lower speaker recognition ratings as seen in Table 16. Finally, one participant reported challenges writing letters using the brush tool since typing text was not a feature available in VR, and another participant reported challenges drawing markups for some elements. This feedback was consistent with observational findings, which showed that participants found it challenging to draw precise 3D markups and often opted to annotate on model surfaces instead.

Table 18: Participant comment examples for supportive VR platform features for team collaboration.

Feature	Comment
Immersion	We felt like we were actually inside the room and saw things clearly.
	Visualizing the model was extremely helpful in seeing where the changes go.
Co-location	It felt like people were there in the room and hence the communication was much simpler.
	All team members can be in one place and communicate by pointing.
Pointer	Pointer was a very efficient tool that helped to point out the changes and problems in the project.
	It was easy to understand and follow what the other team members were saying and suggesting by looking at their pointers
Markup Tool	The markup tool (both shape and brush) with multiple colors allowed me to freely add the design markup and approve the suggested solution.
	The ability to draw my thoughts and mark up the model with my team, and being able to see it in real time as I was doing it. Easy to follow.
Avatar	The movement of the avatar really helped to guide on what the other speaker is talking about and understand the content.
	It was easy to recognize [members] as their names were already mentioned above the avatar.

Analysis of the written responses in Questionnaire B revealed that participants found the VR platform's immersion, co-location, pointer, markup tool, and avatars as useful features supporting their team collaboration. Some examples of the participant comments are presented in Table 18. Some participants reported that VR's immersive environment assisted them in better understanding the design and suggested changes in the alternate design options due to the realistic experience they had, which made them feel as if they were inside the model. Some participants pointed out that the co-location of team members in the virtual space helped with ease of communication. A considerable number of participants reported pointer and markup as efficient tools for communication and supported them in conveying their thoughts, and following what other team members were explaining or suggesting. Finally, some participants reported that the avatar's body language helped with team communication and facilitated the recognition of speakers, which was consistent with observational findings.

Table 19: Participant comment examples for challenging VR platform features for team collaboration.

Feature	Comment
Voice Quality	The VR speakers caused an echo and interfered with communication.
	The voice was lagging at some point.
Avatar	If the speakers changed their location, it was very hard to find them.
	Sometimes the speakers changed their position, and it was difficult to recognize them.
Markup Tool	[Using] brush while typing something
	Marking certain elements was tough.

In summary, participants generally found the immersive and co-located nature of the VR environment, along with visual tools such as pointers and markups, and avatars, highly supportive of collaborative communication. However, limitations related to audio quality and avatar-based speaker recognition presented notable challenges, which may have affected the overall effectiveness of team interactions. These trade-offs provide useful context for interpreting the platform preferences discussed in section 3.4, Platform Preference.

3.4 Platform preference

This section presents the results of the data analysis based on Questionnaire C, in which participants specified their preferred platforms and compared their experiences using BIM and VR for team collaboration. Participants were presented with a series of questions grouped under four categories: spatial understanding and awareness, team communication, visual communication tools, and technical understanding. For each question, they were asked to select whether BIM, VR, or both platforms were most effective in supporting that particular aspect of collaboration. As summarized in Table 20, participants showed a clear preference for the VR platform across most categories. In the spatial understanding and awareness category, 66.7% of participants preferred VR for navigating the model, and 70.0% favored VR for being aware of their location in the model. Preferences were more evenly distributed for understanding the design, with 50.0% preferring VR and 30.0% favoring BIM. In terms of team communication, participants were split between platforms. While 50.0% preferred VR for active collaboration, 33.3% favored BIM. However, when it came to recognizing who was speaking, 36.7% preferred BIM, 40.0% found no difference between platforms, and only 23.3% favored VR. This observation aligns with the findings discussed in the section 3.3.2, VR Platform Features, where participants reported challenges in speaker recognition in the VR environment. For visual communication tools, VR was consistently preferred. A strong majority of participants selected VR over BIM for the effectiveness of the pointer tool, 80.0%, and markup tool, 60.0%. Similar trends were observed for related functions: 80.0% preferred VR for pointing out building components, 76.7% for following a team member's pointer, and 60.0% for both drawing their own markups and understanding others'. Preferences in the area of technical understanding were more mixed. Between 46.7% and 53.3% of participants preferred VR across the four criteria in this category, while BIM was still preferred by a smaller portion, ranging from 33.3% to 43.3%. Notably, for explaining technical constraints and suggesting alternative design options, BIM had a larger share of support compared to other categories, with 40.0% and 43.3% respectively. Overall, participants tended to prefer VR for spatial awareness and visual communication, while preferences for team communication and technical understanding tasks were more distributed across platforms.

Table 20: Participant preferences by platform functionality or function for effective team collaboration (%).

Category	Criteria	BIM	Same	VR
Spatial Understanding & Awareness	Navigate the model.	10.0%	23.3%	66.7%
	Understand the design.	30.0%	20.0%	50.0%
	Be aware of your location in the model.	20.0%	10.0%	70.0%
Team communication	Collaborate actively.	33.3%	16.7%	50.0%
	Recognize team members when they speak.	36.7%	40.0%	23.3%
Visual Communication Tools	Effectiveness of the pointer tool	10.0%	10.0%	80.0%
	Effectiveness of the markup tool	20.0%	20.0%	60.0%
	Be able to point out building components.	16.7%	3.3%	80.0%
	Be able to follow the team member's pointer.	13.3%	10.0%	76.7%
	Be able to draw your thoughts or mark up the model.	26.7%	13.3%	60.0%
	Understand the markups by other team members.	23.3%	16.7%	60.0%
Technical Understanding	Explain your technical constraints.	40.0%	13.3%	46.7%
	Suggest alternative design options to teammates.	43.3%	10.0%	46.7%
	Understand other team members' technical constraints.	33.3%	13.3%	53.3%
	Follow other team members' resolution suggestions.	40.0%	10.0%	50.0%

To further analyze participant platform preferences reported in Questionnaire C, statistical tests were conducted to assess the distribution of responses and identify statistically significant differences in platform preference. In this analysis, a numerical value was assigned to each response for statistical testing: BIM = 1, Same = 2, and VR = 3. Shapiro-Wilk normality test for each criterion was conducted. The results are presented in Table 21. The p-values for all items were well below the significance threshold of 0.05, indicating that the data were not normally distributed. Accordingly, the non-parametric two-tailed Wilcoxon Signed-Rank tests were conducted to evaluate whether preferences for one platform were statistically significant. These tests compared participant responses against a neutral value of 2, which represented no preference between platforms. The results are presented in Table 22, alongside the preferred platform determined by comparing each p-value to the 0.05 threshold. Across the four categories, VR was statistically preferred for nearly all functions. The only exception was recognizing team members when they spoke, where no significant difference emerged between platforms. It should be noted that a separate two-tailed Wilcoxon Signed-Rank test comparing responses to a BIM-preference baseline with the value of 1 yielded a p-value of 0.000117, indicating that participants did not favor BIM and leaned more toward a neutral preference.

Table 21: Shapiro-Wilk test results for participant platform preferences (BIM = 1, Same = 2, and VR = 3).

Category	Criteria	Mean	p-value
Spatial Understanding & Awareness	Navigate the model.	2.4	0.0000001826
	Understand the design.	2.3	0.0000123802
	Be aware of your location in the model.	2.6	0.0000001544
Team communication	Collaborate actively.	2.3	0.0000135809
	Recognize team members when they speak.	1.8	0.0000517190
Visual Communication Tools	Effectiveness of the pointer tool	2.7	0.0000000068
	Effectiveness of the markup tool	2.4	0.0000013705
	Be able to point out building components.	2.8	0.0000000084
	Be able to follow the team member's pointer.	2.7	0.0000000206
	Be able to draw your thoughts or mark up the model.	2.5	0.0000018672
	Understand the markups by other team members.	2.4	0.0000016651
Technical Understanding	Explain your technical constraints.	2.3	0.0000208389
	Suggest alternative design options to teammates.	2.4	0.0000155490
	Understand other team members' technical constraints.	2.4	0.0000074646
	Follow other team members' resolution suggestions.	2.4	0.0000106889

Table 22: Participant platform preferences based on the two-tailed Wilcoxon Signed-Rank test results.

Category	Criteria	p-value	Preference
Spatial Understanding & Awareness	Navigate the model.	0.0123546	VR
	Understand the design.	0.0495346	VR
	Be aware of your location in the model.	0.0002386	VR
Team communication	Collaborate actively.	0.0253473	VR
	Recognize team members when they speak.	0.2513491	Same
Visual Communication Tools	Effectiveness of the pointer tool	0.0000531	VR
	Effectiveness of the markup tool	0.0143059	VR
	Be able to point out building components.	0.0000042	VR
	Be able to follow the team member's pointer.	0.0000877	VR
	Be able to draw your thoughts or mark up the model.	0.0028375	VR
	Understand the markups by other team members.	0.0067144	VR
Technical Understanding	Explain your technical constraints.	0.0184221	VR
	Suggest alternative design options to teammates.	0.0076329	VR
	Understand other team members' technical constraints.	0.0072904	VR
	Follow other team members' resolution suggestions.	0.0046777	VR

Taken together, the results from Questionnaire C indicate a statistically significant preference for the VR platform across nearly all evaluated criteria. Participants favored VR for spatial understanding and awareness, visual communication tools, and technical understanding. Within the team communication category, they preferred VR for active collaboration. The only exception was speaker recognition, where no statistically significant difference was found between the platforms, suggesting that neither offered a clear advantage. These findings highlight the strong potential of immersive VR to enhance remote multidisciplinary AEC collaboration, particularly for tasks requiring shared spatial understanding and visual coordination.

4. CONCLUSIONS

This paper employed a controlled experiment to investigate the effects of immersive VR's avatar body language and 3D markup tools on remote multidisciplinary AEC team collaboration, in comparison to a BIM platform configured with equivalent navigation and communication features. The results showed that teams collaborating in VR reached decisions more quickly than those using the BIM platform, with an average meeting duration reduction of 26.7%. Participants in VR also demonstrated significantly higher consistency in reporting the final team decision, suggesting improved shared understanding. These findings were supported by subjective feedback where participants favored the VR platform for spatial understanding and awareness, the use of visual communication tools, and technical understanding. They also perceived VR as a platform that supported more active collaboration within the team setting. When asked about specific VR platform features, participants highlighted the benefits of the individual pointer and markup tools in communicating technical constraints and reviewing design ideas. They reported that it was easy to follow teammates' markups and pointers during the meetings, and some participants felt that being co-located in the virtual space improved the collaborative experience. Additionally, they reported that the immersive environment helped them better understand the model and perceive the proposed design changes.

Observational analysis showed that avatar body language played a role in team coordination. Participants used head turns to face one another, nods to signal agreement, and hand gestures, such as pointing or waving, to guide teammates or draw attention. Moments of stillness were also observed during periods of focused thinking. These nonverbal cues helped support interaction despite the lack of facial expression and full body language. However, challenges were noted, including difficulty in recognizing who was speaking, which was partly attributed to the lack of directional audio and facial expressions. Observations indicated that participants tended to rely on 2D markups on model surfaces, as creating 3D markups in 3D space was perceived to be more challenging. Because users could move freely within the virtual space, some participants had difficulty locating their teammates during the meeting. In some cases, misunderstandings arose due to limited visibility of where the conversation was focused, such as when a participant followed the discussion from a doorway. These findings highlight that the effectiveness of VR communication depends not only on the platform's features, but also on how participants manage their spatial positioning and maintain visual connection with teammates.

While the BIM platform did not offer the same level of immersion or embodied interaction, participants found that screen sharing helped them stay aligned by allowing everyone to view the model from the presenter's perspective. When sharing their own screen, participants were able to express their design intent clearly using markup tools in Navisworks. However, those who were not sharing their screen had limited ability to communicate visually and had to rely on Zoom's Annotate tool, which was less integrated with the model. In addition, the instability of screen-based markup, such as annotations disappearing or shifting when the view changed, further limited collaborative engagement. This led to a more rigid, turn-based dynamic in teams, reducing opportunities for simultaneous collaboration.

In the prior study using a 3DOF VR platform (Astaneh Asl and Dossick, 2022), some participants experienced disorientation due to limited awareness of where teammates were looking, pointing, or creating markups. In the present 6DOF VR paper, the inclusion of avatar body language cues and 3D markup tools supported clearer spatial communication and reduced these disorientation challenges. The results suggest that adding embodiment and 3D markups in a 6DOF immersive environment may provide incremental benefits for remote multidisciplinary collaboration beyond those observed in 3DOF settings, while acknowledging that the two studies are not directly comparable.

The findings extend beyond perceived advantages of immersive technologies by providing controlled empirical evidence of measurable differences in team performance. For AEC practitioners responsible for technology evaluation and workflow implementation, particularly BIM managers, the results clarify how immersive VR features influence coordination performance compared to conventional BIM-based approaches. For researchers, the paper advances the empirical foundation for understanding how immersive environments affect multidisciplinary collaboration dynamics in remote settings.

While this paper shows promising potential for the use of VR in remote AEC team collaboration, some practical constraints should be considered for real-world adoption. Current safety guidelines for commercial VR headsets recommend limiting continuous headset use time, which may constrain session length in professional settings. In addition, immersive VR requires dedicated, unobstructed physical space for user movement; as a result, practitioners may need to rely more heavily on teleportation or hybrid navigation strategies due to space constraints in typical office environments. Greater reliance on teleportation may introduce additional orientation challenges that warrant further examination. In this paper, sufficient physical space was provided to allow free movement, reducing the likelihood of orientation disruption due to teleportation. Furthermore, real-world deployment should also account for differences in nonverbal cue availability, such as facial expressions in camera-based workflows, which were intentionally controlled in this paper. Considering current technology affordances, the results suggest that immersive VR is best deployed selectively for coordination tasks where shared spatial understanding is critical, complementing existing BIM-based collaboration methods rather than replacing them.

The scenarios in this paper were designed to allow for comparison in a controlled experiment and were not real-world problems. Additionally, the participants were graduate students with a few years of industry experience and exposure to BIM practices. These limitations necessitated that the research team simplify the disciplinary knowledge and define it for each role. Future research studies are recommended to be conducted with AEC professionals to examine how immersive VR can support team collaboration in distributed team settings and assess its potential to reduce meeting durations and improve the team's shared understanding in real-world scenarios. In this paper, pointer and markup tools were examined as part of an integrated immersive collaboration environment that also involved spatial interaction. Separating the effects of these tools from immersion would require a customized non-immersive platform capable of supporting comparable markup and pointer functionality. Future studies are therefore recommended to develop and evaluate such platforms to better understand the independent contribution of these tools to collaborative team performance.

During the experiment, one participant withdrew due to dizziness, a known user response to immersive VR, and another could not wear the headset comfortably due to large-frame eyeglasses despite the use of the headset spacer, highlighting a practical hardware compatibility consideration that can be addressed through alternative eyewear solutions such as contact lenses. In this paper, participants experienced occasional voice echo and had difficulty recognizing speakers, with the lack of directional audio identified as one contributing factor. Future studies are recommended to investigate how spatialized audio and echo cancellation in VR platforms can enhance communication clarity and speaker recognition. Furthermore, conducting similar experiments is recommended using advanced VR hardware capable of capturing facial expressions and full-body movements, once such technology becomes widely available on the market in the future.

ACKNOWLEDGEMENTS

This research study was funded by the California State University, East Bay (CSUEB) Faculty, Scholarship, and Creative Activity (RSCA) Support Grant. The CSUEB's Institutional Review Board issued IRB approval to conduct this research study. We would like to thank Mario Rodriguez for his help with data collection. Thanks to Raji Seelam, Nanditha Nutalapi, and Rhushhab Shah for their contributions to the pilot study conducted one year prior, which helped test and validate the platforms used in this research.

REFERENCES

Abbas A., Choi M., Seo J., Cha S.H. and Li H. (2019). Effectiveness of immersive virtual reality-based communication for construction projects. KSCE Journal of Civil Engineering, Vol. 23, No. 12, 4972–4983. https://doi.org/10.1007/s12205-019-0898-0

Alsuhaibani A., Han B. and Leite F. (2022). Investigating the causes of missing field detected issues from BIM-based construction coordination through semistructured interviews. Journal of Architectural Engineering, Vol. 28, No. 4, 04022028. https://doi.org/10.1061/(ASCE)AE.1943-5568.0000562

Astaneh Asl, B., Attar, W.Z., and Tuscano, T.Z. (2026). Immersive VR versus Desktop for Spatial Understanding of Complex MEP Systems in 3D Coordination Training, Journal of Architectural Engineering, Vol. 32, No. 2, 04026007. https://doi.org/10.1061/JAEIED.AEENG-2052

Astaneh Asl B. and Dossick C.S. (2024). Immersive virtual reality mockup versus physical mockup: effects of immersive virtual environment on AECO team decision-making process, Engineering Project Organization Journal, Vol. 11, No. 1, 20. https://doi.org/10.25219/epoj.2022.00108

Astaneh Asl B., Rummerfield W.N. and Dossick C.S. (2023a). Effects of virtual reality on complex building system recall, Virtual Worlds, Vol. 2, No. 3, 203–217. https://doi.org/10.3390/virtualworlds2030012

Astaneh Asl B., Huynh A.T. and Dossick C.S. (2023b). Immersive VR versus BIM platform features for effective AEC team collaboration, Computing in Civil Engineering 2023, 129–137. https://doi.org/10.1061/9780784485231.016

Astaneh Asl B. and Dossick C.S. (2022). Immersive VR versus BIM for AEC team collaboration in remote 3D coordination processes, Buildings, Vol. 12, No. 10, 1548. https://doi.org/10.3390/buildings12101548

Azarby S. and Rice A. (2022). Understanding the effects of virtual reality system usage on spatial perception: the potential impacts of immersive virtual reality on spatial design decisions, Sustainability, Vol. 14, 10326. https://doi.org/10.3390/su141610326

Balin S., Bolognesi C.M. and Borin P. (2023). Integration of immersive approaches for collaborative processes with building information modeling (BIM) methodology for the AEC industry: an analysis of the current state and future challenges, Virtual Worlds, Vol. 2, No. 4, 374–395. https://doi.org/10.3390/virtualworlds2040022

Bhonde D., Zadeh P. and Staub-French S. (2022). Evaluating the use of virtual reality for maintainability-focused design reviews. Journal of Information Technology in Construction, Vol. 27, 1–20. https://doi.org/10.36680/j.itcon.2022.013

Castronovo F., Nikolic D., Liu Y. and Messner J. (2013). An evaluation of immersive virtual reality systems for design reviews, Proceedings of the 13th International Conference on Construction Applications of Virtual Reality (CONVR 2013), University College London, London, UK, October, Vol. 47. https://eres.scix.net/pdfs/convr-2013-2.pdf

Cruz-Neira C., Sandin D.J., DeFanti T.A., Kenyon R.V. and Hart J.C. (1992). The CAVE: Audio visual experience automatic virtual environment, Communications of the ACM, Vol. 35, No. 6, 64–72. https://doi.org/10.1145/129888.129892

Dey C., Grabowski M., Frontzkowski Y., MP G. and Ulbrich S. (2024). Social virtual reality: systematic review of virtual teamwork with head-mounted displays, Journal of Workplace Learning, Vol. 36, No. 7, 569–584. https://doi.org/10.1108/JWL-02-2024-0049

Dossick C.S. and Neff G. (2011). Messy talk and clean technology: communication, problem-solving and collaboration using building information modelling. Engineering Project Organization Journal, Vol. 1, 83–93. https://doi.org/10.1080/21573727.2011.569929

Du J., Shi Y., Zou Z. and Zhao D. (2018). CoVR: cloud-based multiuser virtual reality headset system for project communication of remote users. Journal of Construction Engineering and Management, Vol. 144, No. 2, 04017109. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001426

Du J., Zou Z., Shi Y. and Zhao D. (2018). Zero latency: real-time synchronization of BIM data in virtual reality for collaborative decision-making. Automation in Construction, Vol. 85, 51–64. https://doi.org/10.1016/j.autcon.2017.10.009

Du J., Shi Y., Mei C., Quarles J. and Yan W. (2016). Communication by interaction: a multiplayer VR environment for building walkthroughs. In: Construction Research Congress 2016, 2281–2290. https://doi.org/10.1061/9780784479827.227

Eastman C., Teicholz P., Sacks R. and Liston K. (2011). BIM handbook: A guide to building information modeling for owners, managers, designers, engineers and contractors, 2nd ed., John Wiley & Sons, Hoboken, NJ. ISBN: 978-0470541371

Feldstein I.T., Kölsch F.M. and Konrad R. (2020). Egocentric distance perception: a comparative study investigating differences between real and virtual environments, Perception, Vol. 49, No. 9, 940–967. https://doi.org/10.1177/0301006620951997

Fischer M. (2006). Formalizing construction knowledge for concurrent performance-based design, Intelligent Computing in Engineering and Architecture, Lecture Notes in Computer Science, Vol. 4200, Springer, Berlin, Germany, 186–205. https://doi.org/10.1007/11888598_10

Fogarty J., McCormick J., El-Tawil S. (2018). Improving student understanding of complex spatial arrangements with virtual reality. Journal of Professional Issues in Engineering Education and Practice, Vol. 144, No. 2, 04017013. https://doi.org/10.1061/(ASCE)EI.1943-5541.0000349

Girgin S., Fruchter R. and Fischer M. (2024). Analyzing attributes and objectives of MEP buildability issue descriptions: a comparison of VR and non-VR. In ASCE International Conference on Computing in Civil Engineering 2024, Carnegie Mellon University, Pittsburgh, PA. https://doi.org/10.1061/9780784486122.034

Haahr M.T. and Knak H.B. (2023). Multi-user virtual reality-based design review of students' construction designs. In Digitalization in Construction, 1–19. Routledge. https://doi.org/10.1201/9781003408949-1

Heinonen M., Lahtinen J., Hannula T. and Peltokorpi A. (2022). Evaluating the benefits of collaborative VR review for maintenance documentation and risk assessment, Applied Sciences, Vol. 12, No. 14, 7155. https://doi.org/10.3390/app12147155

Heydarian A., Carneiro J.P., Gerber D., Becerik-Gerber B., Hayes T. and Wood W. (2015). Immersive virtual environments versus physical built environments: a benchmarking study for building design and user-built environment explorations. Automation in Construction, Vol. 54, 116–126. https://doi.org/10.1016/j.autcon.2015.03.020

Johansson M. and Roupé M. (2024). Real-world applications of BIM and immersive VR in construction. Automation in Construction, Vol. 158, 105233. https://doi.org/10.1016/j.autcon.2023.105233

Kelly J.W. (2022). Distance perception in virtual reality: a meta-analysis of the effect of head-mounted display characteristics, IEEE Transactions on Visualization and Computer Graphics, Vol. 29, No. 12, 4978–4989. https://doi.org/10.1109/TVCG.2022.3196606

Khanzode A., Fischer M. and Reed D. (2008). Benefits and lessons learned of implementing building virtual design and construction (VDC) technologies for coordination of mechanical, electrical, and plumbing (MEP) systems on a large healthcare project, Journal of Information Technology in Construction, Vol. 13, 324-342. http://www.itcon.org/2008/22

Kim S., Billinghurst M. and Kim K. (2020). Multimodal interfaces and communication cues for remote collaboration. Journal on Multimodal User Interfaces, Vol. 14, No. 4, 313–319. https://doi.org/10.1007/s12193-020-00346-8

Korman T.M., Fischer M.A. and Tatum C.B. (2003). Knowledge and reasoning for MEP coordination, Journal of Construction Engineering and Management, Vol. 129, No. 6, 627–634. https://doi.org/10.1061/(ASCE)0733-9364(2003)129:6(627)

Kuliga SF., Thrash T., Dalton R. and Hölscher C. (2015). Virtual reality as an empirical research tool – exploring user experience in a real building and a corresponding virtual model. Computers, Environment and Urban Systems, Vol. 54, 363–375. https://doi.org/10.1016/j.compenvurbsys.2015.09.006

Liston K., Fischer M. and Winograd T. (2010). Focused sharing of information for multidisciplinary decision making by project teams, Journal of Information Technology in Construction, Vol. 6, 69–82. http://www.itcon.org/2001/6

Liu Y., Castronovo F., Messner J. and Leicht R. (2020). Evaluating the impact of virtual reality on design review meetings, Journal of Computing in Civil Engineering, Vol. 34, No. 1, 04019045. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000856

Lu J., Fu C., Zhou T., Xie J. and Loo Y.M. (2022). A review of physical and digital mock-up applications in healthcare building development, Buildings, Vol. 12, No. 6, 745. https://doi.org/10.3390/buildings12060745

Majumdar T., Fischer M.A. and Schwegler B.R. (2006). Conceptual design review with a virtual reality mock-up model, Proceedings of the Joint International Conference on Computing and Decision Making in Civil and Building Engineering, Montréal, Canada, June, 2902–2911.

http://www.irbnet.de/daten/iconda/CIB21113.pdf

Maldovan K.D., Messner J.I. and Faddoul M. (2006). Framework for reviewing mockups in an immersive environment, Proceedings of the 6th International Conference on Construction Applications of Virtual Reality (CONVR 2006), Orlando, FL, USA, March, Vol. 6. https://itc.scix.net/pdfs/6d87.content.04272.pdf

Mehrbod S., Staub-French S. and Tory M. (2019). BIM-based building design coordination: processes, bottlenecks, and considerations, Canadian Journal of Civil Engineering, Vol. 47, No. 1, 25–36. https://doi.org/10.1139/cjce-2018-0287

Messner J., Anumba C., Dubler C., Goodman S., Kasprzak C., Kreider R., Leicht R., Saluja C. and Zikic N. (2021). BIM project execution planning guide, Version 3.0, Computer Integrated Construction Research Program, The Pennsylvania State University, University Park, PA, USA. https://psu.pb.unizin.org/bimprojectexecutionplanning/

Muthumanickam NK., Brown N., Duarte JP. and Simpson TW. (2023). Multidisciplinary design optimization in architecture, engineering, and construction: a detailed review and call for collaboration. Structural and Multidisciplinary Optimization, Vol. 66, No. 11, 239. https://doi.org/10.1007/s00158-023-03673-y

O'Donnell F.J. and Duffy A.H.B. (2002). Modelling design development performance, International Journal of Operations & Production Management, Vol. 22, No. 11, 1198–1221. https://doi.org/10.1108/01443570210450301

Paes D., Irizarry J. and Pujoni D. (2021). An evidence of cognitive benefits from immersive design review: Comparing three-dimensional perception and presence between immersive and non-immersive virtual environments. Automation in Construction, Vol. 130, 103849. https://doi.org/10.1016/j.autcon.2021.103849

Pietroforte R. and Tombesi P. (2010). Physical mockups as interface between design and construction: a North-American example, Proceedings of the CIB 2010 World Congress, Salford, UK, 95–107. https://www.irbnet.de/daten/iconda/CIB18864.pdf

Prabhakaran A., Mahamadu A.M. and Mahdjoubi L. (2022). Understanding the challenges of immersive technology use in the architecture and construction industry: a systematic review. Automation in Construction, Vol. 137, 104228. https://doi.org/10.1016/j.autcon.2022.104228

Rafsanjani HN. and Nabizadeh AH. (2023). Towards digital architecture, engineering, and construction (AEC) industry through virtual design and construction (VDC) and digital twin. Energy and Built Environment, Vol. 4, No. 2, 169–178. https://doi.org/10.1016/j.enbenv.2021.10.004

Rigutti S., Stragà M., Jez M., Baldassi G., Carnaghi A., Miceu P. and Fantoni C. (2018). Don't worry, be active: how to facilitate the detection of errors in immersive virtual environments. PeerJ, Vol. 6, e5844. https://doi.org/10.7717/peerj.5844

Sacks R., Eastman C., Lee G. and Teicholz P. (2018). BIM handbook: a guide to building information modeling for owners, designers, engineers, contractors, and facility managers, 3rd ed., John Wiley & Sons, Hoboken, NJ. ISBN: ISBN: 978-1-119-28753-7

Sateei S., Roupé M. and Johansson M. (2025). From informative to co-design: the role of immersive virtual reality for user involvement in healthcare facility design, Journal of Information Technology in Construction, Vol. 30, No. 32, 778–806. https://doi.org/10.36680/j.itcon.2025.032

Sateei S., Roupé M. and Johansson M. (2022). Collaborative design review sessions in virtual reality: multi-scale and multi-user. In: Proceedings of the 27th International Conference of the Association for Computer Aided

Architectural Design Research in Asia (CAADRIA), Sydney, Australia, 9–15. https://doi.org/10.52842/conf.caadria.2022.1.029

Scrivener S.A., Ball L.J. and Tseng W. (2000). Uncertainty and sketching behaviour. Design Studies, Vol. 21, 465–481. https://doi.org/10.1016/S0142-694X(00)00019-3

Shi Y., Du J., Lavy S. and Zhao D. (2016). A multiuser shared virtual environment for facility management. Procedia Engineering, Vol. 145, 120–127. https://doi.org/10.1016/j.proeng.2016.04.029

Staub-French S. and Khanzode A. (2008). 3D and 4D modeling for design and construction coordination: issues and lessons learned, Journal of Information Technology in Construction, Vol. 13, 261–274. http://www.itcon.org/2007/26

Tatum C.B. and Korman T.M. (1999). MEP coordination in building and industrial projects, CIFE Working Paper No. 54, Center for Integrated Facility Engineering, Stanford University, Stanford, CA, USA. https://stacks.stanford.edu/file/druid:vn180wh3959/WP054.pdf

Tea S., Panuwatwanich K., Ruthankoon R. and Kaewmoracharoen M. (2022). Multiuser immersive virtual reality application for real-time remote collaboration to enhance design review process in the social distancing era. Journal of Engineering, Design and Technology, Vol. 20, No. 1, 281–298. https://doi.org/10.1108/JEDT-12-2020-0500

Truong P., Hölttä-Otto K., Becerril P., Turtiainen R. and Siltanen S. (2021). Multi-user virtual reality for remote collaboration in construction projects: a case study with high-rise elevator machine room planning. Electronics, Vol. 10, No. 22, 2806. https://doi.org/10.3390/electronics10222806

Tüker C., Tong T. (2021). Comparing field trips, VR experiences and video representations on spatial layout learning in complex buildings. arXiv preprint arXiv:2105.01968. https://doi.org/10.48550/arXiv.2105.01968

Ververidis D., Nikolopoulos S. and Kompatsiaris I. (2022). A review of collaborative virtual reality systems for the architecture, engineering, and construction industry. Architecture, Vol. 2, No. 3, 476–496. https://doi.org/10.3390/architecture2030027

Wahlström M., Aittala M., Kotilainen H., Yli-Karhu T., Porkka J. and Nykänen E. (2010). CAVE for collaborative patient room design: analysis with end-user opinion contrasting method, Virtual Reality, Vol. 14, No. 3, 197–211. https://doi.org/10.1007/s10055-009-0138-x

Wen J. and Gheisari M. (2020). Using virtual reality to facilitate communication in the AEC domain: a systematic review, Construction Innovation, Vol. 20, No. 3, 509–542. https://doi.org/10.1108/CI-11-2019-0122

Westerdahl B., Suneson K., Wernemyr C., Roupé M., Johansson M. and Allwood C.M. (2006). Users' evaluation of a virtual reality architectural model compared with the completed building, Automation in Construction, Vol. 15, No. 2, 150–165. https://doi.org/10.1016/j.autcon.2005.02.010

Wolfartsberger J. (2019). Analyzing the potential of virtual reality for engineering design review. Automation in Construction, Vol. 104, 27–37. https://doi.org/10.1016/j.autcon.2019.03.019

Wu S., Stendal K. and Thapa D. (2024). Emerging trends in XR-mediated virtual team collaboration in digital workspaces: a systematic literature review. Advances in Information Systems Development: Information Systems Development, Organizational Aspects, and Societal Trends, 85–108. https://doi.org/10.1007/978-3-031-57189-3_5

Zaker R. and Coloma E. (2018). Virtual reality-integrated workflow in BIM-enabled projects collaboration and design review: a case study. Visualization in Engineering, Vol. 6, No. 1, 4. https://doi.org/10.1186/s40327-018-0065-6

Zhang Y., Liu H., Kang S.C. and Al-Hussein M. (2020). Virtual reality applications for the built environment: research trends and opportunities, Automation in Construction, Vol. 118, 103311. https://doi.org/10.1016/j.autcon.2020.103311