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Immersive VR versus BIM for AEC Team Collaboration in Remote 3D Coordination Processes

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Abstract: Building Information Modeling (BIM) and Virtual Reality (VR) are both tools for collaboration and communication, yet questions still exist as to how and in what ways these tools support technical communication and team decision-making. This paper presents the results of an experimental research study that examined multidisciplinary Architecture, Engineering, and Construction (AEC) team collaboration efficiency in remote asynchronous and synchronous communication methods for 3D coordination processes by comparing BIM and immersive VR both with markup tools. Team collaboration efficiency was measured by Shared Understanding, a psychological method based on Mental Models. The findings revealed that the immersive experience in VR and its markup tool capabilities, which enabled users to draw in a 360-degree environment, supported team communication more than the BIM markup tool features, which allowed only one user to draw on a shared 2D screenshot of the model. However, efficient team collaboration in VR required the members to properly guide each other in the 360-degree environment; otherwise, some members were not able to follow the conversations.

Keywords: virtual reality (VR); building information modeling (BIM); 3D coordination; clash resolution; remote collaboration; multidisciplinary AEC team

Citation: Astaneh Asl, B.; Dossick, C.S. Immersive VR versus BIM for AEC Team Collaboration in Remote 3D Coordination Processes. *Buildings* **2022**, *12*, 1548. https://doi.org/10.3390/buildings12101548

Academic Editor: Svetlana J. Olbina

Received: 31 August 2022
Accepted: 21 September 2022
Published: 27 September 2022

1. Introduction

Advances in information and communication technologies provide opportunities for Architecture, Engineering, and Construction (AEC) professionals to collaborate remotely. These technologies support collaboration in distributed teams and save the travel time to meetings for face-to-face interaction. Construction projects require the coordination of different AEC disciplines with complex representations of design and analysis. In general, AEC project stakeholders use Building Information Modelling (BIM) at different phases of a facility's life cycle to insert, extract, update, or modify information to support and reflect the stakeholders' roles [1]. With effective collaboration and management strategies, BIM brings value to construction projects by reducing the field interferences, increasing productivity, reducing rework, requests for information (RFIs), change orders, and cost growth [2]. In particular, the 3D coordination process that begins from the design phase and is carried out through the construction phase accomplishes this value by enabling the project team to resolve the field conflicts before installation [2,3]. This process requires the multidisciplinary collaboration of the designers and builders, both the exchange of models as well as discussion and negotiation around how these disciplines intersect. Per our prior observational studies, typically the critical building system conflicts that require different project stakeholders' involvement to be resolved are discussed in 3D coordination meetings. The rest of the system conflicts are coordinated asynchronously [4].

Research has shown that while BIM tools support problem definition, the support for team members' dialogues to brainstorm and create shared knowledge to resolve problems and make decisions is less clear [5]. To brainstorm and collaborate, AEC team members draw, write, sketch, or talk together [5]. In common practice in the 2010s, BIM-based remote 3D coordination meetings, BIM was shared synchronously on a 2D shared screen where only one person has control over the view and the pointer and can create markup on the model. This made team engagement and collaboration more challenging than face-to-face meetings, where team members could discuss through pointing and sketching together. To create annotations in the asynchronous 3D coordination process, AEC professionals draw markup and add comments as texts on the 2D screenshot of the 3D model. This brought some limitations in terms of communication, as the snapshot may not capture all the required digital information [4].

The AEC industry has recently seen a growth in the use of innovative technologies, including Extended Realty (XR), which is an umbrella term for technologies like Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality [6]. Despite AR and MR that present the digital content in the physical environment, VR provides a digital world that makes it a practical tool for remote collaboration. Unlike BIM, which presents 3D models on 2D screens, VR provides an environment for the user to be immersed in the model. The immersive VR experience can be created with a head-mounted display (HMD) or projected systems where the model is projected on a curved screen or the sides of a large cube [7]. In recent years, HMD hardware has become more affordable and available for individual use in the market, while projected VR systems are expensive and require a large space to install, and are time-consuming to maintain. Projected VR systems also require the project teams to meet physically. This makes the use of HMD preferable for the industry and a practical tool for remote collaboration. Unlike BIM software packages where features are already defined within the program, VR content can be created in gaming engines like Unity [8], that allows the creators to add customized features to the interface. Some VR systems enable the users to share the virtual space and draw together in a 360-degree environment. In asynchronous collaboration, some VR systems allow users to record messages with voice while using the markup tool to draw to explain system conflicts and resolutions. In this case, the user who receives the message can still explore the model while the markup is being created in the recording. As compared to typical BIM interfaces, the VR markup in these systems is dynamic while BIM's is fixed on the 2D screenshot of the model and disappears when the user wants to explore the model. While there is renewed interest in using VR for remote collaboration, there remain questions about how this technology can support technical collaboration in design and construction teams such as 3D Coordination.

The studies on VR for AEC collaboration are mainly conducted on design review, a process that starts from the planning phase and ends before the start of the construction [2], which does not necessarily require the construction team's involvement. These studies have a focus on the end-user experience or communication of the design by professionals with non-technical clients [9–17]. Sateei et al. (2022) recently conducted a study in which HMD was utilized for the architectural design review of a school project. The users were given tools to create markup, measure dimension, and take snapshots in VR. The participants found these tools helpful in collaborating and understanding each other's point of view and spatial reasoning [18]. In a research study, VR's application for 3D coordination was explored, where the Mechanical, Electrical, and Piping (MEP) system review was led by a BIM modeler and an MEP installer using HMD. In this study, the virtual model was explored to check pipeline conditions, clashes between MEP and architectural and structural systems, the installation process, and the adequacy of space for equipment maintenance. The participants had positive feedback on using VR for 3D Coordination and suggested adding a markup tool to the VR interface to make it more practical [19]. In a research study conducted with avatar-based desktop VR enabled with markup tool, teams had more mutual discoveries of design issues in VR in comparison to BIM. In this study, project participants collaborated in remote virtual meetings, where globally distributed architecture and construction teams were tasked to perform design review. Teams could draw markup together to convey their thoughts and highlight design problems. However, the virtual team setting was similar to BIM-based practices, where markup was created on a 2D screenshot of the model [20]. From this prior research VR supports the creation of shared understanding and is an effective method to convey technical information across a diverse group of people. What is not yet understood is how markup tools in the 3D coordination processes effect multidisciplinary AEC team collaboration efficiency.

In this study, to measure the team's collaboration efficiency, a psychological method called Shared Understanding was utilized. Team members represent the understanding of their environment in the form of Mental Models. Mental Model elicitation methods capture the research-related concepts and their relationship in the individual Mental Model [21]. The shared concepts and links among the team members' Mental Model structures represent Shared Mental Model or Shared Understanding [22]. Shared Understanding in the context of AEC collaboration is the phenomenon where team members have a mutual understanding of the disciplinary requirements and constraints to discuss design options and make decisions [23]. The common Mental Model elicitation methods used in psychology are observation, questionnaires, interview, content analysis, and card sorting [21,23]. Mental Models were studied in the AEC industry in the design teams, that included engineering and architecture design creativity [24] and Shared Understanding between the architects and clients [25]. In this study, we focused on Shared Understanding between the designers and builders. We designed this research project to study the effects of VR's immersive environment and markup tool capabilities on the multidisciplinary AEC team's Shared Understanding in the remote 3D coordination processes.

Background

Drawings are traditionally created using Computer-Aided Drafting (CAD) software that automates the manual drafting process. The trade coordination process is then performed by sequentially comparing transparent drawings for each system generated from CAD over a light table to find the conflicts between different building systems. This process requires frequent meetings. Visualizing complex building systems in this method is difficult, and accommodating design changes are challenging [26]. Due to the inefficiency of this process, numerous conflicts often remain undetected and must be addressed in the field, which is costly [27]. With the introduction of BIM to the AEC industry, teams spend less time in coordination meetings using BIM compared to the paper-based processes and have more satisfying coordination processes [27,28]. In the 3D coordination processes using BIM, the authoring software creates scaled, parametric, and object-oriented 3D models for building systems [29]. BIM review software combines different building system models into a single model, called the federated model, and determines the conflicts between the systems using the clash detective tool by comparing their 3D models [3,30]. Although BIM has facilitated the 3D Coordination processes by automating the detection of clashes between building systems, it requires the AEC project stakeholders to collaborate and resolve them [31].

In the last two decades, the use of VR for collaboration has increased in the AEC industry. VR is a technology that can simulate the reality human beings experience. It's a computer-generated environment that can give the user an illusion of being in a virtual world. Power wall and CAVE are projected-base VR technology where the model is projected on large screens. In power wall, large screens are set in a way that they create a curved screen. In CAVE, model is projected on the walls of the room-sized cube [7]. Researchers have used these technologies for face-to-face team collaboration on the design review of university facilities [9], hospital patient rooms [10], and courtrooms [11,12] as well as scheduling of a nuclear power plant [13]. Liu et al. (2020) conducted a research study on thirteen design review meetings where various visualization media like 2D drawings, BIMs, and renderings supported the team collaboration in projected VR [17]. Research studies with HMD has been mainly focused on single users with no team interactions. A limited number of studies has focused on multi-user HMD VR that includes the design review of university facilities [14,15], residential and commercial buildings [16], and a school [18], as well as design review and 3D Coordination of an office building [19] and scheduling of various construction projects [32]. Truong et al. (2021) studied remote VR collaboration for the construction planning of elevator machine rooms. Users were equipped with tools such as free hand drawing, cube drawing, measuring tool, and camera. Participants were asked to identify the installation challenges, use the free hand drawing tool to mark them up, and then capture the VR scenes with the camera tool. Participants reported utilizing multi-user VR system to be preferred over teleconferencing for collaboration [33]. Markup tool was used in only two of these studies on the AEC team collaboration in the multi-user VR platform [18,33].

The 3D Coordination processes require the AEC project stakeholders to collaborate and resolve the conflicts between the building systems by exchanging disciplinary knowledge while they vet design alternatives. Project team members have in-depth knowledge in the areas of their expertise, but they share a part of their knowledge understandable by other team members in explaining design ideas, disciplinary constraints, and technical analysis to collaborate, find solutions, and make decisions. This phenomenon is referred to as Shared Understanding. Prior studies suggest that Shared Understanding is highly desirable for interdisciplinary teams as it has a positive effect on team performance [34,35], team member satisfaction [34], coordination of activities among team members [36], innovation [37], reduction of iterative loops and rework [38], and team morale [39]. There remains the question of how technology tools like BIM and VR can support teams to build Shared Understanding in the 3D coordination processes.

2. Materials and Methods

To study the effects of VR's immersive environment and markup tool capabilities on technical AEC collaboration, controlled experiments were designed to compare the markup enabled immersive VR platform with BIM, which was the control platform. Two experiments of A and B were designed to study the asynchronous and synchronous team collaboration, respectively. Experiment A was developed to study the individual's Mental Model of technical knowledge communicated in a one-to-one asynchronous collaboration. Experiment B was designed to study Shared Understanding at a team level in synchronous collaboration. The technical information in the experiments was controlled. Study participants were provided role-specific technical information and were required to collaborate based on the given technical knowledge. To assess Shared Understanding, the research team used observation and questionnaire methods. The observation method allowed the research team to track conversations to elicit individual Mental Models and Shared Understanding. It also allowed for the study of how users utilized the markup tool and interacted with the digital interface. With the questionnaire method, the users' immediate responses after the experiment were captured while using the interview method had some limitations in this regard. The questionnaires were designed in a way that they captured the individual's understanding of the technical information and team decision. They also provided an opportunity for the study participants to give feedback on their experiences.

2.1. Participants

The experiment participants were twenty-four University of Washington (UW) graduate students enrolled in a graduate-level Virtual Construction course in the Department of Construction Management. In the first week of the class, students' educational background, industry experience, and previous experience with BIM and VR were surveyed to assist in grouping them into comparable teams to reduce the effects of background experience on the results. Students' educational backgrounds were mainly in architecture and civil engineering. The average industry work experience of the participants was three years. Six students had worked as 3D modelers in the industry. They were either exposed to some VR or did not have any previous experience. Participants were taught BIM and

VR skillsets for seven weeks with a main focus on model navigation, design review and 3D coordination. During this time, teams were given a term project that required them to get to know each other, work in a team setting, and build a team relationship. Experiments A and B were given as homework and in-class activity assignments in the eighth week of the class, respectively.

2.2. Digital Setup

The digital platforms of BIM and VR were designed in a way that they provided the same features for the users except for the markup tools that were unique for each platform and immersion in VR. For the BIM platform, Autodesk Navisworks [40] was installed on PCs and allowed users to navigate the models and review them using tools like commenting and markup. A mobile Application (App) developed by a startup company was utilized for the VR platform. The VR App offered a cloud-based virtual collaboration platform that provided a color-coded markup tool. The VR App was installed on smartphones, and the immersive VR content was viewed through glasses called Viewer attached to the smartphone. This App supported three degrees of freedom (3DOF). Meaning, it tracked the head orientation and enabled the users to look around while they were virtually fixed in one location. The users looked at a static 360-degree spherical image using the App. Autodesk Navisworks' navigation tool provided six degrees of freedom (6DOF) to the user and allowed them to both look around and walk around inside the model. To design a controlled experiment, there was a need to set up the BIM platform in a way that it provided the same 3DOF experience in VR as for the BIM users. For this purpose, viewpoints were created in the middle of the model spaces. The viewpoint in Autodesk Navisworks is the 3D snapshot taken of the model as it displays in the screen view. The viewpoints were created from the eye level of an avatar with a height of 5 feet and 6 inches. Participants were allowed to use the navigation tool of Look Around to explore the model in the defined viewpoints and use the Review tool to create markup. The field of view in BIM review software was set to 90 degrees to replicate the same field of view in VR. The VR content was created using the Rendering tools in Autodesk Navisworks. A static 360-degree spherical photo was captured at the location of each viewpoint from the same eye level in BIM. To create a markup, users should have touched the smartphone screen and drew by head movement. If the cellphone screen remained untouched for a few seconds, the markup would disappear. Users could explore the model in VR by head rotation while they were required to use a computer mouse in the BIM platform to explore it on desktop. The digital setup is discussed in more detail for each experiment in their relative section.

2.3. Experiment A: Asynchronous Collaboration

Experiment A was designed to evaluate the efficiency of VR platform features in an asynchronous 3D coordination process. This experiment studied the effects of two variables of VR's voice and dynamic markup in the 360-degree environment on one-to-one individual communications in comparison to text and markup on the 2D screenshot of the 3D model in BIM. The individuals' understanding of the annotations created for communicating building system conflicts and resolution as well as the efficiency of the VR features for communicating the conflicts and proposing alternative design options by the study participants to other team members were evaluated. The research study was set up based on the federated model of the new Burke Museum building on the UW Seattle campus. The project's general contractor, Skanska, provided this model for educational and research purposes to the research team. The building's mechanical room was selected as the experiment space, which had complex MEP systems.

2.3.1. Scenarios

Two scenarios of A and B were designed for this experiment. In Scenario A, the study participants received the digital files in both BIM and VR platforms in which a conflict of building systems and the resolution were described. In the second scenario, the study participants were asked to create markups and communicate another system conflict and the resolution using BIM and VR features.

Scenario A

In the first scenario, the structural engineer increased the depth of two structural beams which caused clashes with the pipelines passing underneath. The BIM manager informed the piping subcontractor to revise the model by dropping pipelines down based on the mechanical engineer's recommendation. The first beam, called Beam 1, clashed with two branches of hot water pipelines. The piping subcontractor should drop the main hot water pipes along with the branches eight inches down to prevent the system conflict. The second beam, called Beam 2, clashed with a group of pipelines, including the main hot water pipelines, whose branches clashes with Beam 1. The piping subcontractor should drop down the group of pipelines resting on the hanger for six inches, while the main hot water line should still be dropped eight inches due to the clash with Beam 1. The structural beams were located in two different parts of the mechanical room. A location relatively close to both clash groups was designated in the model. When fixed in this location facing one clash group, the user needed to turn around approximately 90 degrees to see the other clash group. These clash groups are shown in Figure 1. In this figure, the clash group of Beam 1 with the pipeline is called Clash 1, and the clash group of Beam 2 with the pipeline is called Clash 2.

Scenario B

In the second scenario, Beam 2 clashed with the mechanical ductwork. Participants were asked to take the BIM Manager's role and create annotations in both platforms of BIM and VR to explain the cause of this clash to the mechanical subcontractor. Then, point out the ductwork's bend in another location in the model and ask the subcontractor to resolve the clash by dropping the duct further at the bend. Figure 1 shows the location of the duct's bend and the clash of the duct with Beam 2, which is called Clash 3. Participants needed to turn around approximately 150 degrees in the model to see the location of the duct bend when facing the clash.

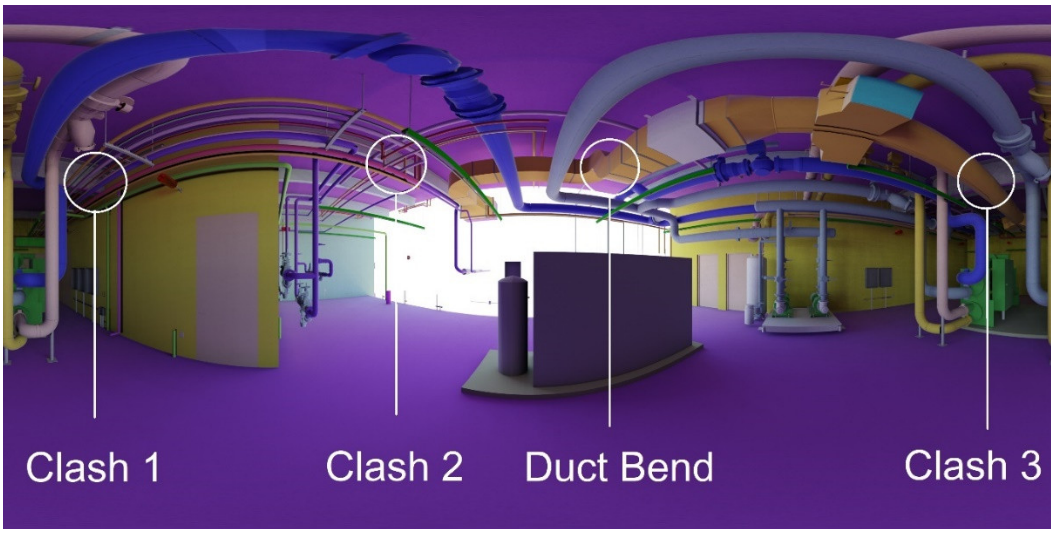

Figure 1. Clash groups in Experiment A.

2.3.2. Digital Setup

To communicate the cause of the clash groups, their relevance to each other, and the required action for resolving the clashes in the BIM platform, two viewpoints were created in the BIM platform for clashes 1 and 2. Participants could click on each of the viewpoints in Saved Viewpoints window to see the annotations. The explanation was given as text in the Autodesk Navisworks' Comments section, and the model was marked up using its Review tool. The markup's color was selected to be cyan to match the VR App's default color code. Since annotations were created on a 2D snapshot of the model, if participants moved in the model using navigation tools, the annotation would disappear. To see the annotations again, they had to click on the saved viewpoints. Figure 1 shows the expanded 360-degree spherical photo captured from the same location and eye level in BIM, and Figure 2 shows the annotations created in two viewpoints in the BIM interface. In the VR platform, a cloud-based message was recorded in which the same explanations typed in the Autodesk Navisworks' Comments section were communicated by voice while a dynamic markup was created highlighting system conflicts and resolutions as the explanation was provided. The markup drawings were the same as the ones created in the BIM platform. Figure 3 provides snapshots of the recorded message in VR. The study participants could explore the model in the 360-degree environment while receiving the message. There was a need to guide them in the environment to know in which direction they should look to see the markup. For this purpose, the message asked them to look at the dialogue box in the VR interface, and they were then guided with markups from there.

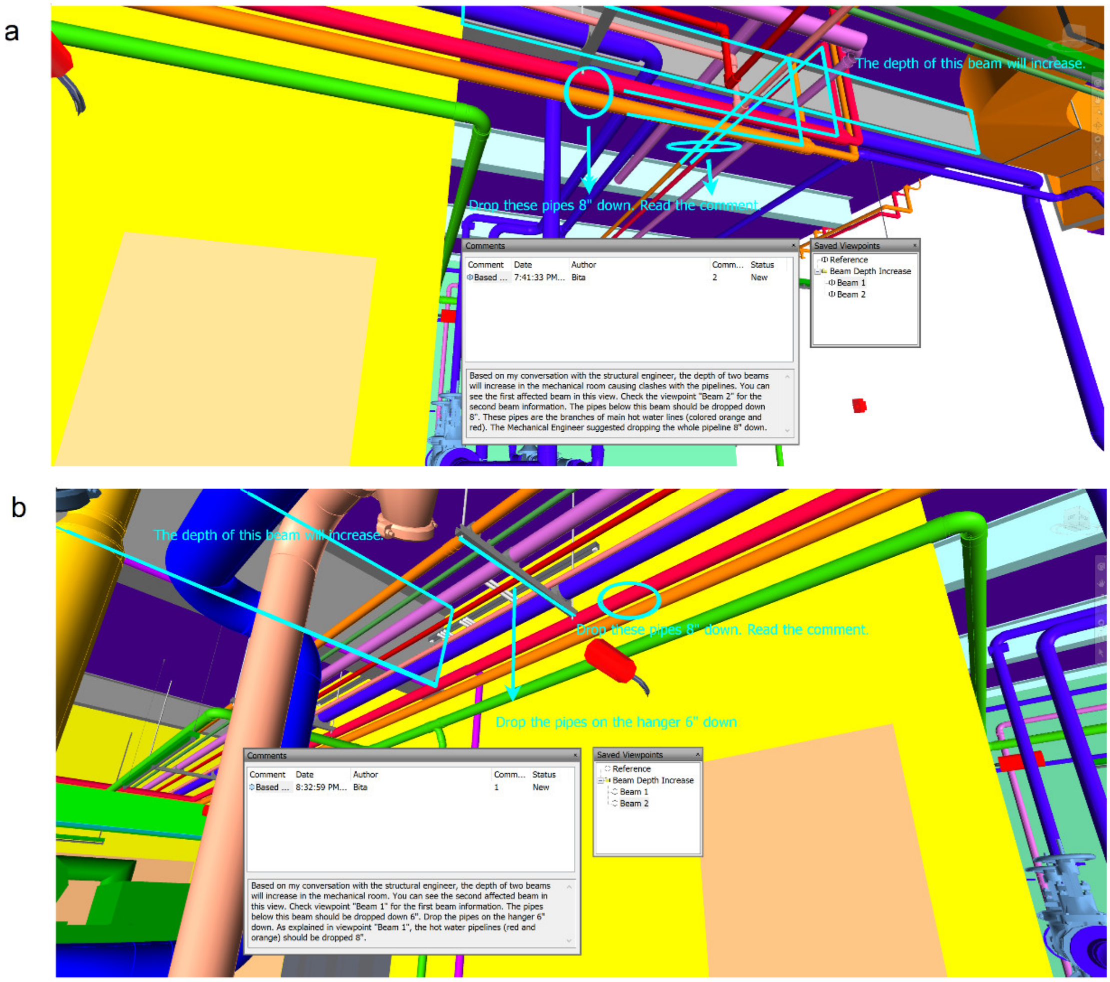

Figure 2. Annotations in the BIM platform for: (**a**) Clash 1; (**b**) Clash 2.

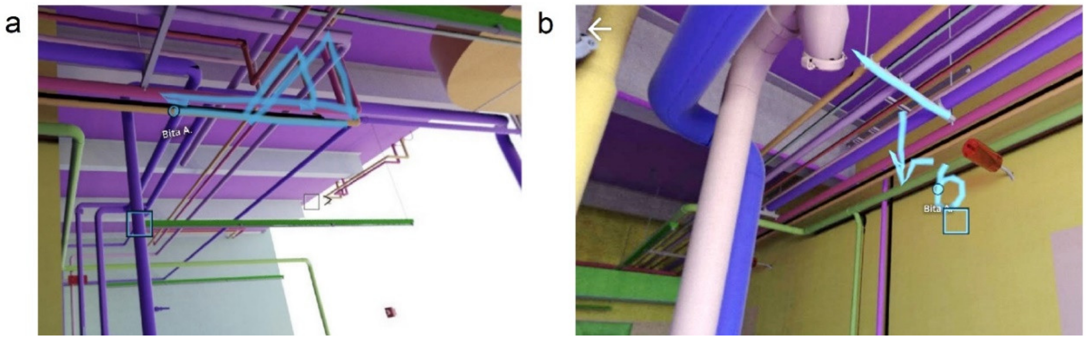

Figure 3. Screenshots of the recorded message in VR, explaining: (**a**) Clash 1; (**b**) Clash 2.

2.3.3. Procedure

Study participants were divided into two groups named BV and VB based on the sequence to which they were exposed to the models. For instance, Group BV was asked to check the annotations in the BIM platform first and then switch to VR. Each participant had received a BIM file and a meeting ID for the VR App to explore the annotations related to the conflict of structural beams with pipelines. They were then asked to compare the annotations in two platforms and explain which one they preferred to understand the building system conflicts and resolution. In the second part of the experiment, participants created annotations in both platforms based on the sequence defined by their Group name to communicate the clash of the duct with beam and its resolution to the mechanical subcontractor. They used the same BIM file to create viewpoints and markups. In the VR platform, they recorded their message by replying back to the message they originally have received in the VR App. Participants were then asked to give feedback on their experience and the preferred platform features that supported their technical communication. Figure 4 presents the procedure schematically.

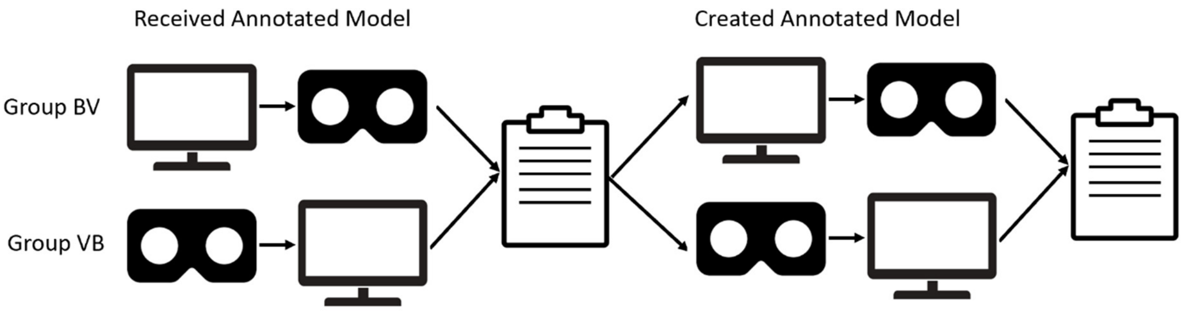

Figure 4. Experiment A—Asynchronous Collaboration's procedure.

2.4. Experiment B: Synchronous Collaboration

The Experiment B design was based on the collaboration of four team members with different AEC roles of the architect, structural engineer, mechanical subcontractor, and piping subcontractor. Two comparable scenarios were created in which the structural design changes were affecting the scope of other disciplines in the project. Team members were asked to exchange disciplinary knowledge to find an alternative design option to accommodate the structural design changes. Teams had the opportunity to work in both BIM and VR platforms. The disciplinary information was provided to each team member based on their specific role in the team for the purpose of controlling the exchanged knowledge content. To evaluate individual's understanding of the exchanged disciplinary knowledge and team decision, or in other terms Mental Model concepts, questionnaires were designed and given to the participants at the end of the meeting in each platform.

Participants were asked to fill out another questionnaire at the end of the experiment to reflect on their experience in two platforms. The 3D coordination meetings were video recorded for the observational study purpose. Since facial expressions was not captured in VR, participants were prohibited from sharing videos and were only allowed to communicate with voice.

2.4.1. Scenarios

Two comparable scenarios with the same number and type of technical constraints were designed based on a hypothetical research facility where mechanical and piping equipment in the mechanical room serve the laboratories (Labs). In the first scenario, Scenario A, the mechanical room, and the Labs are located on the same floor where the duct and pipes run horizontally. In the second scenario, Scenario B, the mechanical room, and the Labs are located at two different levels, and the duct and pipes run vertically. The details of both scenarios are as follows.

Scenario A

In the first scenario, a part of the southern zone of the research facility was presented to the participants, as seen in Figure 5a. One air handler and two boilers located in the mechanical room serve Lab B on the east side of the plan. The duct and the pipes exit the mechanical room and enter the East corridor, which has a ceiling soffit to embed the duct and pipes. They enter Lab B from the North corridor. The structural engineer is assigned to inform the team that the East wall of the mechanical room and the Lab office with the total length of 40 ft needs to be a shear wall based on the structural analysis. As a result, the opening area in this wall should be limited. Otherwise, a structural failure could happen. In the original design, there are three openings in the wall: one for the door, one for the duct, and one for two pipes. The opening area should be limited to only one opening, either for one duct or two pipes, and the door needs to be relocated. To relocate the mechanical room door, the architect notes that it can be located on the West wall to use the West corridor. The door has to be located in either the corners or middle of the West wall of the mechanical room right behind one of the boilers or the air handler. The architect also informs the team that the Lab office was previously designed as a storage room. As a result, no ceiling soffit was considered for this room. The owner does not want to pay for the ceiling soffit. If the subcontractors want to route the duct and pipes through the Lab office, a corner soffit needs to be installed, which is cheaper than the ceiling soffit. Each corner soffit can embed either one duct or two pipes and should be along the East or West wall of the Lab office. The cost for the 20 ft corner soffit is USD 1500 for two pipes and USD 2000 for a duct. The mechanical subcontractor warns the team that due to the sensitivity of Lab A to vibration, no MEP system should be placed in the West corridor. Based on the mechanical subcontractor's conversation with the mechanical engineer, by moving the air handler to the East wall and routing it from the East corridor, they needed to spend an extra USD 2000 to buy a more powerful air handler since it needs to push the air through two consequent duct bends. The piping subcontractor reminded the team that the ceiling height is low. As a result, the duct and the pipe could not be installed at different heights. No piping or ductwork could go above the door. If the subcontractors changed their routing, they needed to make sure the duct route ended at the same point where the current duct and pipe were in the Lab. The ductwork and piping cost USD 50/ft and USD 25/ft, respectively. Subcontractors could only use 90 degrees bends. They should also consider maintenance areas for their equipment providing approximately 10 feet of clearance. Meaning if they line all equipment on one wall, two pieces of equipment should be located at the corners and one in the middle of the wall. The architect prefers to have both the boilers and the air handling unit on one wall of the mechanical room so that the owner can use the rest of the room space for storage since the storage room was turned into the Lab office. The owner preferred to spend less than USD 2000 on all the changes the team makes to the design.

Scenario B

In Scenario B, another zone of the research facility was presented to the experiment participants, as seen in Figure 5b. The mechanical room and the storage room were located on the first floor, and the Lab and the Lab office were on the second floor. The structural engineer was assigned to inform the team that the Lab on the second floor had heavy equipment, which results in a high shear force applied to the slab underneath. During the design review process, the structural team had realized the two slab openings provided by the mechanical and piping subcontractor for the pipe and duct risers in the Lab floor slab would result in structural failure. By pouring a thicker concrete slab, the structural engineer could allow one opening in this slab for either one duct or two pipes. Pouring a thicker slab would result in a USD 2000 extra cost based on the conversation with the general contractor. The slab below the Lab office on the second floor could have a maximum of two openings, one opening for one duct, and one opening for two pipes. A large opening for both the duct and two pipes would result in structural failure. The architect did not prefer the MEP routing to be seen in the Lab office, but it could be seen in the storage room. The architect preferred to have the openings in the slab on the corners of one wall so that the MEP system could be embedded in the corners of a wall-to-wall cabinet. The owner had already accepted paying for the cabinet in the Lab office, but the location of this cabinet was not specified yet. If the team decides to embed the MEP system in the cabinet, some cabinet space would be occupied that could not be used. The team needed to consider USD 500 extra cost for embedding one duct or two pipes in the corner cabinets for installation and occupying the usable space. The architect preferred to have both the boilers and the air handler on one wall of the mechanical room so that the owner could use the rest of the room space for storage. Since one storage room became a Lab office, as explained in Scenario A, the owner needed to use the mechanical room space for storage. Adding a duct bend to the current route results in USD 500 extra cost. The same constraints of ceiling height, routing over door, maintenance area, and routing angles are applied in Scenario B. The ductwork and piping cost USD 50/ft and USD 25/ft, respectively. The owner preferred to spend up to USD 4000 for all the changes team made to the design.

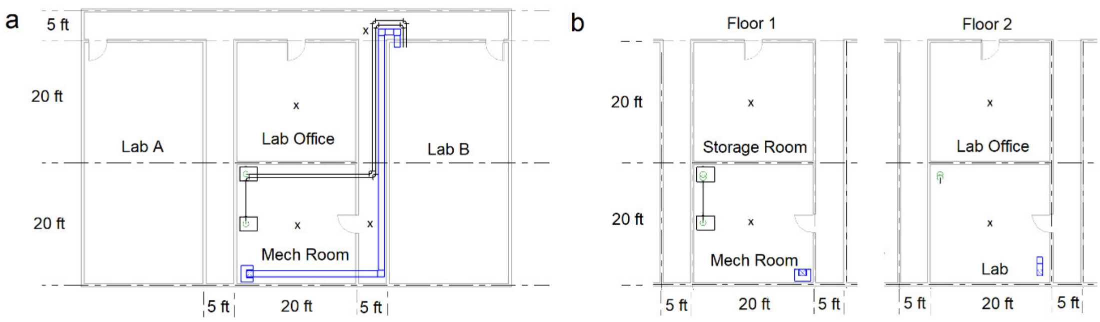

Figure 5. Scenario plans: (**a**) Scenario A plan; (**b**) Scenario B plans for floors 1 and 2.

Alternative Design Options

The intended solution to accommodate the structural design changes in Scenario A was to move all the equipment to the North wall of the mechanical room, and move the door to the West wall. They could put the air handler on the Northeast corner and route the duct from the East corridor and route the pipes from the soffit. Another acceptable option was to put the air handler on the Northwest corner, route the duct from the Lab office and route the pipes from the East corridor or with a more expensive option route them both from the Lab office. The intended solution to accommodate the structural design changes in Scenario B was to keep the air handler in its current location, move the door to the West wall, move the boilers to the East wall and route them from the storage room and then up to the Lab office, embed them in the cabinet, and then route them into the Lab. They could also move all the equipment to the West wall, route the pipes as previously explained, and add a bend to the duct. This would cost slightly above the budget due to the extra pipe length for routing from the storage room, which was considered negligible. Participants had various options to move the equipment and reroute the piping and ductwork to meet the technical requirements of the scenarios, however, only the design alterative options explained above met the budget.

2.4.2. Questionnaires

To capture each participant's understanding of the exchanged technical information and team's final decision, four questionnaires were designed. The Questionnaires AA and BA were given at the start of the scenarios A and B team meetings, respectively. These questionnaires contained empty drawings of the facility that only showed the architectural layout on the plan and elevation. Participants were asked to individually draw the alternative design based on the final team decision on the drawings at the end of the meeting. These questionnaires were the tool to measure if the individual shared the same understanding of the selected design option with other team members. Questionnaires AB and BB were distributed after the participants filled out Questionnaires AA and BA, respectively. These questionnaires had two parts. The first part asked the participants to answer technical questions to measure the individuals' understanding of the technical requirements and constraints of other disciplines. The second part of the questionnaires required the participants to reflect on their experience and write about the platform features that were helpful in terms of communicating the technical information, suggesting solutions, and making the final team decision. They were also asked to reflect on the platform features that prevented them from working efficiently. Questionnaire C was distributed at the end of the experiment to ask the participants to reflect on their experience in the two platforms and compare the efficiency of their team collaboration using BIM and VR.

2.4.3. Digital Setup

Two 3D models of architectural and mechanical were created using Autodesk Revit [41]. Autodesk Navisworks was then utilized for combining both into a federated model for use in the experiment. Four viewpoints were created shown as "x" on the plans in Figure 5. To prevent users from changing location in BIM platform, a wall was created as a boundary around the user in the architectural model using Autodesk Revit. Then, by utilizing the Visibility tools in Autodesk Navisworks, the wall was set as a transparent object. To enable users to share their screen in the BIM platform, Zoom [42], a cloud-based conferencing software for remote online meetings was used. The VR App provided a color-coded markup tool for virtual meeting attendees. Teleportation was defined to link the viewpoints to enable the users to toggle between them in VR to explore the model. In virtual meetings, users saw the pointer of each other as a small circle with their name next to it. Figure 6 shows the expanded 360-degree spherical photo of the mechanical rooms in scenarios A and B.

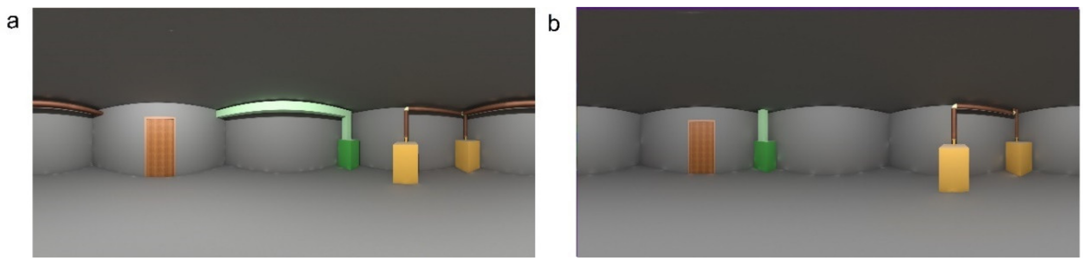

Figure 6. Expanded 360-degree spherical photo of the mechanical rooms: (**a**) Scenario A; (**b**) Scenario B

2.4.4. Physical Setup

In the BIM platform, each participant was provided a computer with access to the internet, two monitors, and a headset. Providing two monitors to the participants enabled them to have their own individual viewpoint to locally explore and mark up the model in one monitor while viewing another team member's shared screen on the second monitor, which replicated the individual viewpoint in VR. Video conferencing was not allowed, and students used headphones to communicate verbally via audio conferencing. In the VR platform, participants were asked to use their smartphones and headphones. The research team provided VR Viewers to the participants to attach to their smartphones. Team members communicated verbally via audio conferencing using their phones while sharing the same digital space in VR.

2.4.5. Procedure

Six participating groups were named based on the platform sequence. Group BV1, BV2, and BV3 started from the BIM platform, and groups VB1 VB2, and VB3 collaborated in the VR platform first. Groups were asked to work on Scenario A to find an alternative design to accommodate the structural design change. Participants were given time before the start of their meeting to read their role-specific technical information and explore the model individually, either in BIM or VR platforms depending on the group name, to have a full understanding of the assignment description and the model. The Questionnaire AA was distributed before the start of the meeting. Team members in the BIM platform joined the meeting using the Zoom's meeting link that was already setup. The meeting was recorded with the Zoom's recording feature. Participants using VR, logged in to the App by entering the meeting ID, and joined the meeting. They all called a phone number to join an audio conference using their smartphone. The audio of the meeting and the screen of the observer's smartphone was recorded. At the end of the meeting, team members filled out the Questionnaire AA. They were then given Questionnaire AB to answer. To work on Scenario B, groups switched platforms. They met online on the second platform, and the process was repeated with Questionnaires BA and BB. At the end of the experiment, Questionnaire C was distributed to capture the participants' reflection on their experiences in both platforms. Figure 7 presents the procedure schematically.

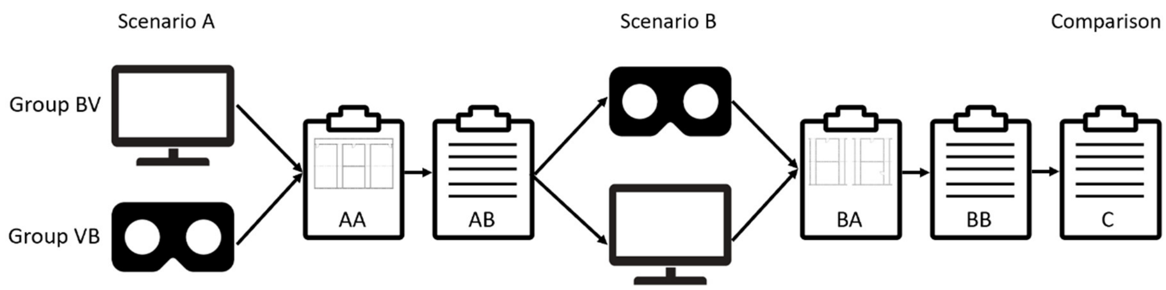

Figure 7. Experiment B—Synchronous Collaboration's procedure.

3. Results

3.1. Experiment A: Asynchronous Collaboration

Experiment A's results are described in two sections that explain VR features' efficiencies for understanding the technical information communicated with annotations by the participants and the use of these features by participants for communicating technical information to other team members. The results are summarized in Table 1 and are presented with bar charts in Figure 8.

Table 1. Participants' platform preferences to understand and create annotations.

Groups	Understand Annotation		Create Annotation	
	VR	BIM	VR	BIM
BV	83.3%	16.7%	58.3%	41.7%
VB	75.0%	25.0%	50.0%	50.0%
Total	79.2%	20.8%	54.2%	45.8%

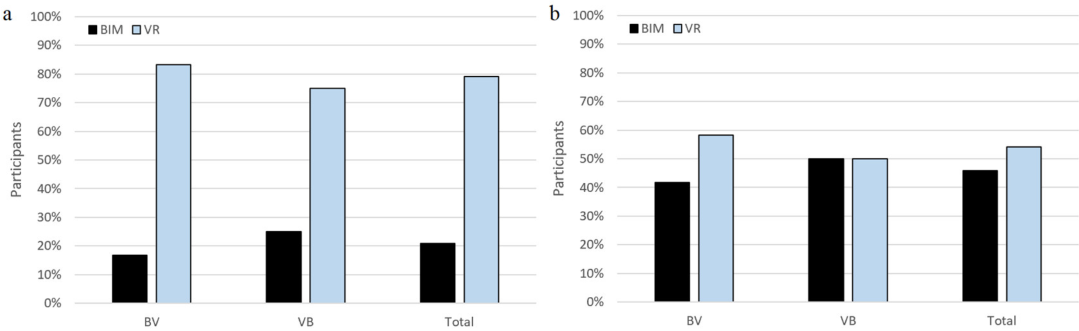

Figure 8. Participants' platform preferences to: (**a**) understand annotations; (**b**) create annotations.

3.1.1. Understanding the Annotation

The results from the participants' feedback analysis show that 83.3% of the Group BV and 75.0% of the Group VB, with a total of 79.2% found VR a preferred platform over BIM to understand the annotations that explained the clashes between the pipelines and two structural beams and the proposed resolution. Based on their survey results, it was easier for them to follow the dynamic annotations, and they found the voice an efficient way of communication over text to understand the annotations in a shorter time. Since they were able to explore the model while the markup was created, and the explanation was given in the message, they were able to understand the correlation between the clash groups. Some participants in Group BV reported that it took them some time to understand the connection between two annotations in BIM while it was much easier for them to recognize it in VR. The remaining 21%, five participants, reported BIM as the preferred platform in this practice. One participant stated that he personally prefers text over voice to understand a context. Another participant indicated having a hard time following the voice message and had to replay it to catch up. Three of the remaining participants reported that since they had a better understanding of the space in BIM, it helped them understand the annotations, and their preference was regardless of the VR markup tool capabilities. Participants who preferred the VR's markup tool, also reported that VR's immersive environment helped them understand the location of the clashes and their relevance to each other. Some mentioned having a better sense of the depth in VR assisted in understanding the interferences of the systems. There was also a note from a participant regarding people with disabilities who have difficulties in hearing that may not be able to use the VR audio features.

3.1.2. Creating the Annotation

Participants' reflections on their experience in creating an annotation in both platforms to communicate the clash cause and resolution to the project team were also analyzed. The results show that 58.3% of the Group BV, and 50.0% of Group VB, with a total of 54.2% voted for VR as a preferred platform to communicate their technical work. Participants who preferred the VR platform reported they had to create two annotations in BIM to communicate the cause of the clash and the resolution, while in VR, they could create markup in the 360-degree environment and explain both in one message. They also found the voice a faster way to communicate the technical work instead of typing the comment as text. Most of the participants who preferred BIM over VR indicated having a hard time drawing in VR. Some had to record the message multiple times to create a clean drawing, while BIM's annotation tool gave them the ability to draw clean markups. Another reported drawback was that in BIM, they could easily erase a markup or change a text if they made mistakes, but in VR, they had to create a new recording to correct themselves. Some found it hard to keep in mind that they needed to guide the audience in the 360-degree environment so that when other team members checked the message, they knew where to look. Although the software's interface had an arrow that pointed out the location where the markup was being created, the observational study results showed that the message receiver might be disoriented without proper guidance in the 360-degree environment.

3.2. Experiment B: Synchronous Collaboration

The accuracy of the proposed design alternative by groups in both platforms of BIM and VR are presented in Table 2. In Scenario A, two groups of BV2 and BV3 proposed the optimal design option in the BIM platform. Group BV3 moved all equipment to the North wall of the mechanical room where the air handler was located on the Northeast corner, routed the duct from the East corridor, and the pipes from the soffit on the East wall of the Lab office. To prevent the conflict of the pipes and the duct, they put a gap between the North wall and the air handling unit and did not relocate the door. This alternative design was not optimal with respect to the use of mechanical room space, but since the air handling unit was located in a dead space between the door and the North wall that could not be used for storage, and the design satisfied all other requirements, their proposal was accepted. Among the teams in the VR platform, Group VB1 found the optimal design alternative, and Group VB2's proposal was very close to one of the acceptable design options. In Scenario B, none of the groups in BIM could resolve the conflict based on the disciplinary constraints as they altered the scenario requirements. In the VR platform, two groups of BV1 and BV3 arrived at the correct alternative design, and Group BV2's response was very close to the acceptable design option. It should be noted that Groups BV1 and BV3 moved all the equipment to the West wall of the mechanical room, and they were slightly above the budget, which was considered negligible.

Table 2. Group performance in the platforms of VR and BIM.

Group	Accuracy of Design Alternative		MD (min:sec)		SUD_1 (min:sec)		SUD_2 (min:sec)	
	VR	BIM	VR	BIM	VR	BIM	VR	BIM
BV1	Correct	Incorrect	24:06	32:32	11:01	18:42	13:05	13:50
BV2	Incorrect	Correct	28:36	48:53	22:42	36:30	05:54	12:23
BV3	Correct	Correct	30:45	48:39	24:56	35:09	05:49	13:20
VB1	Correct	Incorrect	32:56	23:33	20:39	07:57	12:17	15:36
VB2	Incorrect	Incorrect	28:10	19:32	19:24	07:07	08:46	12:25
VB3	Incorrect	Incorrect	40:33	43:42	13:31	15:29	27:02	28:13

—MD where the proposed design was the optimal design alternative; —MD where the proposed design was close to the optimal design alternative.

3.2.1. Technical Knowledge Exchange

In all meetings, teams started with icebreaker conversations. Then, they began exchanging the technical information to come to a Shared Understanding of the structural design change and disciplinary constraints. The official start of the meeting was considered from the time the first disciplinary knowledge was exchanged to eliminate the icebreaker conversations at the beginning of the meetings. Team members had different styles in providing their disciplinary knowledge to other team members. Some members clearly defined the constrains at the beginning of the meeting. Some revealed them whenever the suggested design alternative had a conflict with their scope of work. Furthermore, a few of the members withheld information from the team. They also had different approaches to provide the reasoning of why the restrictions existed. Some members clearly explained the reasoning behind each constraint, while another group of participants provided the reasoning only when a curious member asked about the logic behind it. As a result, most team members were not able to answer all the questions in Questionnaires AB and BB since some technical information was never shared within the team. Consequently, the questionnaire results were only used for qualitative analysis to determine each team member's understanding of the technical information shared in the team.

3.2.2. Team Member Participation

Two different types of member participation in the team were observed, Active and Passive. Active members were actively participating in the team conversations, proposing a design alternative, or challenging the proposed design. Passive members exchanged their disciplinary knowledge and constraints and answered other members' questions whenever they needed disciplinary information or clarification, but they did not actively participate in the team conversation to find a solution. The activity type of each team member is presented in Table 3. There was a total of fifteen Active and nine Passive members in the experiment. The analysis of Questionnaires AB and BB data show that Passive members could answer the questions related to their disciplines, but their correct responses to the questions regarding other discipline's scope of work were lower in comparison to Active members.

Table 3. Team member performance.

Group	Member	Activity Type	Accurate Report of Team Decision									
			Boiler Location		Piping Route		Air Handler Location		Ductwork Route		Total (%)	
			VR	BIM	VR	BIM	VR	BIM	VR	BIM	VR	BIM
BV1	Architect	Active	x	x	x	x	x	x	x	x	100%	100%
	Structural Eng	Passive *	x		x		x		x		100%	0%
	Mechanical Sub	Passive	x	x	x		x	x	x		100%	50%
	Piping Sub	Active	x	x		x	x	x	x	x	75%	100%
BV2	Architect	Active	x	x	x	x	x	x	x	x	100%	100%
	Structural Eng	Passive	x	x	x	x		x			50%	75%
	Mechanical Sub	Active	x	x	x	x	x	x	x	x	100%	100%
	Piping Sub	Passive	x		x		x		x		100%	0%
BV3	Architect	Active	x	x	x	x	x	x	x	x	100%	100%
	Structural Eng	Active	x	x	x	x	x	x	x	x	100%	100%
	Mechanical Sub	Active	x	x	x	x	x	x	x	x	100%	100%
	Piping Sub	Active	x	x	x	x	x	x	x	x	100%	100%
VB1	Architect	Active	x	x	x	x	x	x	x	x	100%	100%
	Structural Eng	Passive	x	x		x	x	x		x	50%	100%
	Mechanical Sub	Active	x	x	x	x	x	x	x	x	100%	100%
	Piping Sub	Active	x	x	x	x	x	x		x	75%	100%
VB2	Architect	Active	x	x	x	x	x	x	x	x	100%	100%
	Structural Eng	Passive	x	x			x	x	x	x	75%	75%
	Mechanical Sub	Active	x	x	x	x	x	x	x	x	100%	100%
	Piping Sub	Passive	x	x	x	x	x	x	x	x	100%	100%
VB3	Architect	Active	x	x	x	x	x	x	x	x	100%	100%
	Structural Eng	Active	x	x	x	x	x	x	x	x	100%	100%
	Mechanical Sub	Passive	x	x	x	x	x	x	x	x	100%	100%

Piping Sub	Passive	x	x			x	x		50%	50%
								Average	90.6%	85.4%

* Performed as a Passive member using BIM and more like an Active member in VR.

3.2.3. Duration to Reach Shared Understanding

One specific trend was observed in all teams. Team members began the meeting with exchanging information and suggesting alternative design options up to the point that an Active member came to a Shared Understanding with all team members on the disciplinary constraints and suggested the final design alternative. This Active member then explained the desired design option and discussed it with other Active members. The Active members then asked the Passive members if they understood the final decision, or the Passive members asked the Active members to give a summary of the final design or answer some clarifying questions. To analyze the data, three parameters were defined, as seen in Table 2. The meeting duration, MD, is the duration between the time when one member starts to exchange the first disciplinary information, T_{Start}, and the time at the end of the final conversation when all team members confirmed they have a clear understanding of the team decision, or an answer to a clarifying question regarding the final design alternative was given, T_{End}. Two parameters for the duration of building Shared Understanding were defined. The time the Active member spent to build a Shared Understanding of the disciplinary constraints is called SUD_1, and the time each team spent to build the Shared Understanding of the final design alternative is called SUD_2. The moment the Active member starts to propose the final design alternative, T_{BM}, was used as the benchmark for the calculations.

$$MD = T_{Start} - T_{End} \quad (1)$$

$$SUD_1 = T_{BM} - T_{Start} \quad (2)$$

$$SUD_2 = T_{End} - T_{BM} \quad (3)$$

The SUD_1 parameter is not only dependent on the platform features but is also dependent on the way team members exchanged information. As previously discussed, individuals showed different approaches in revealing their disciplinary knowledge. SUD_1 is also dependent on the accuracy of the exchanged information and the Active member's awareness of all disciplinary requirements, while SUD_2 was mainly affected by the platform features and was a good measure for team performance comparison in two platforms. Figure 9 presents the comparison of SUD_2 values for both platforms with bar charts. The durations of the correct design alternatives are highlighted in Table 2. The durations of the meetings that resulted in a solution close to the optimum design are also highlighted with a lighter color. Considering the Scenario A, two groups of BV2 and BV3 found the optimal design alternative using BIM within approximately forty-nine minutes, while Group VB1 resolved the conflict within about thirty-three minutes. Group VB2, whose proposed solution was close to the acceptable design option, finished the meeting within twenty-eight minutes. Considering Scenario B, only two groups, BV1 and BV3, proposed the correct design alternative in VR after spending about twenty-four and twenty-eight minutes, respectively, in the meeting, which is close to what was observed in the team performance of Group VB1 in the VR platform.

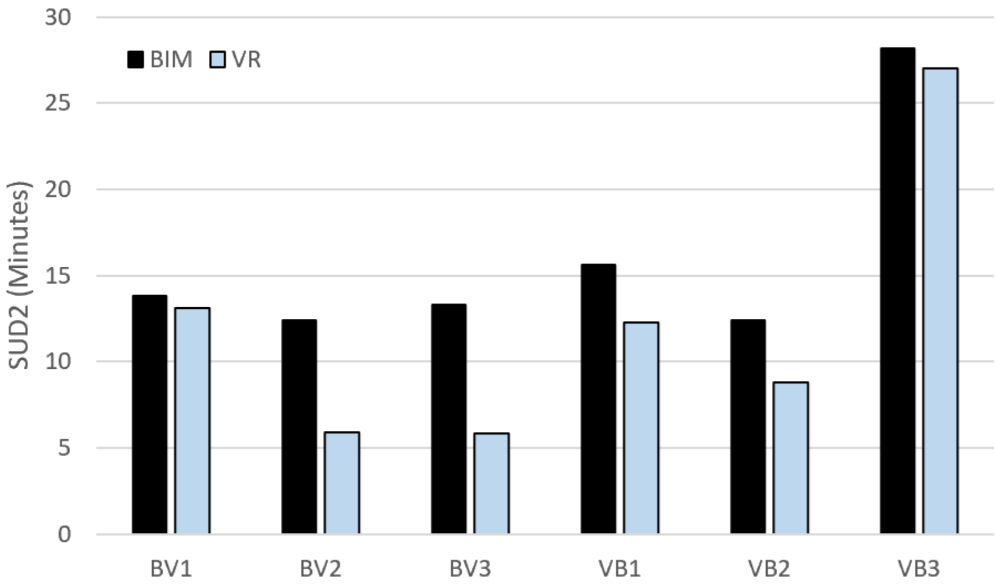

Figure 9. Time spent by each group in two platforms of BIM and VR to build Shared Understanding of the alternative design.

3.2.4. Team Performance

This section describes the approach of teams and team members toward exchanging disciplinary knowledge, building Shared Understanding, and finding the optimum design alternative for each scenario in two platforms of BIM and VR. Table 3 summarizes the team members' participation type, as well as the accuracy of reporting the team's decision. The correct report of boiler and air handler locations, as well as piping and ductwork routings are specified with "x" in the table based on the responses to Questionnaires AA and BA. On average, members' reported team decision accuracy was slightly higher in VR compared to BIM.

Group BV1

Group BV1 had two Active members in the BIM platform, the architect and the piping subcontractor. The structural engineer was not able to communicate the structural constraints to the team in Scenario A where the BIM view was under the control of the piping subcontractor. All other team members thought one big opening in the shear wall was acceptable to allow both the pipes and the duct to go through, while the structural engineer was not aware of this misunderstanding. Questionnaire AB results show that the structural engineer had a full understanding of the structural requirements. Based on the Questionnaire AA results, the final design alternative reported by the structural engineer was meeting the structural constraints and was different from the team's final decision. Additionally, the mechanical subcontractor reported the piping and duct routes incorrectly. In Scenario B, the architect took the lead on the team and was considerably more active in comparison to Scenario A, where the control of the shared screen was with the piping subcontractor. The structural engineer performed more like an Active member, could communicate the disciplinary restrictions, and created markup to join the team conversation. The team suggested the optimal alternative design, and all members reported the team decision correctly except the piping subcontractor who misunderstood the routing of the pipes. The piping subcontractor had a hard time understanding the model in VR and consequently, the proposed design. The team spent some extra time to help this member understand the alternative design. As a result, the time they spent to come to a Shared Understanding of the final design, SUD_2, was close to the time spent in BIM.

Group BV2

Group BV2 had two Active members; the architect, and the mechanical subcontractor. In Scenario A, the architect's screen was shared with all team members. Active members reported the final decision correctly. The structural engineer routed the duct from the West corridor, which was prohibited. Neither the location of the boiler nor the piping and duct routing was reported correctly by the piping subcontractor. In Scenario B, the proposed alternative design was not satisfying the requirement for keeping all equipment on one wall of the mechanical room. The piping route, which was the challenging part of Scenario B, was designed correctly. The team was aware of the equipment location requirement but forgot to apply it when they made the final decision. Group BV2 was the only team that did not use markup in VR to communicate their disciplinary work or the final decision. Instead, they all met virtually and guided each other to look at a specific location in the model and use their imagination to understand the proposed design. While the piping subcontractor could not report the final decision correctly in the BIM platform, this team member reported the alternative design correctly in VR and reported VR's immersive environment helped in understanding the design. The structural engineer did not report the location of the air handler and routing of the duct correctly. Considering the fact that this group was close to find the correct design alternative in the VR platform, the parameters could be compared in both platforms. Parameters of MD and SUD_1 are significantly lower in VR in comparison to BIM. With regard to SUD_2, the time they spend in VR to build the Shared Understanding of the final design alternative among team members was less than 50% of the time they spent in the BIM platform.

Group BV3

Group BV3 was the only team with four Active members. They proposed acceptable design alternatives for both scenarios. Moreover, they all reported the team decision correctly in the questionnaires in both platforms. In Scenario A, all team members got the chance to share their screen and actively collaborated. In Scenario B, all team members used the markup tool to collaborate in VR and finally proposed the optimal design alternative. Group BV3 spent 37% less time in the meeting, 29% less time to come to a Shared Understanding of the design constraints, and 56% less time to build the Shared Understanding of the final design alternative in VR in comparison to BIM.

Group VB1

All members of Group VB1 were Active except the structural engineer. They started from Scenario A in VR and proposed the correct design alternative. The piping subcontractor, who was an Active member, reported the routing of the duct incorrectly. The structural engineer only specified the location of the equipment correctly but did not draw the pipeline and ductwork routes. In Scenario B, the architect did not share the reasoning of why the equipment should be placed on one wall of the mechanical room. The team decided to move the equipment to the Lab office and assumed the wall of the mechanical room and Lab office could be considered as one wall. They misunderstood the Scenario assumptions and worked on a simplified problem. This explains why SUD_1 has a considerably low value in VR in comparison to BIM. On the other hand, it took them an extra 26% of the time they spent in VR to bring everyone to the same Shared Understanding in the BIM platform. All team members could answer the team's decision correctly in the Questionnaire BB, and both the piping subcontractor and the structural engineer could follow the team conversations.

Group VB2

Group VB2 had two Active member; the architect, and the mechanical subcontractor. This team had the lowest meeting duration among six groups for both scenarios. The passive members clearly defined their disciplinary constraints, but the Active members shared less information to the team and mostly proposed solutions that did not have a conflict with their scope of work. The architect never shared the restriction regarding the location of the equipment. As a result, the proposed design alternatives did not meet this criterion. In VR, they routed the pipes and ducts from the East corridor and the soffit in the Lab correctly, and only the equipment location did not meet the requirement for the storage space as the equipment was located on two walls. They only needed to move the air handler to the Northeast corner with no extra cost, which was already discussed in the team. Group VB2's meeting took 28:10, while Group VB1 spent 32:56 to find the optimal design alternative. If Group VB2 were aware of the equipment location constraints, they might have been able to find the correct design option within a similar amount of time as Group VB1. In Scenario B, since the team was not aware of the equipment location requirement, they made the same mistake as Group VB1 and relocated the equipment to the Lab office and worked on a simplified problem. This explains the low value for SUD_1 that is very close to Group VB1's value. Regarding SUD_2, they spent 32% more time in BIM to build a Shared Understanding of the final team decision in comparison to VR. All team members reported the team's final decision correctly in both platforms except the structural engineer, who misunderstood the pipeline routing in both scenarios.

Group VB3

Group VB3 had long meetings in both platforms. The meeting conversations revealed that they did not start their meetings well prepared as they did not spend the time before the experiment to read the guidelines and role-specific technical information and explore the model to be familiar with the project. They had two Active members; the architect, and the structural engineer. In Scenario A, they routed the duct from the West corridor, where they were not allowed to place any MEP system due to the sensitivity of the Lab to vibration. The mechanical subcontractor had informed them of this requirement but did not warn them when they made the final decision to use this corridor for routing. In Scenario B, the team decided to move the Lab office cabinet to the Lab and worked on a different scenario. All team members reported the final decision in both platforms correctly.

3.2.5. Collaboration Challenges

The results of the observational study show that team members had challenges in both VR and BIM platform to follow the team conversations. In the BIM platform, some members were not aware of the building locations where the other team member was pointing or creating markup on the shared screen. When team members started sharing the screen, in the beginning, they asked if everyone could see their screen. However, they did not ask for their confirmation during the meeting. In VR platform, on the other hand, each time markup was created in the environment, most of the markup creators asked the team to confirm they could see the markup, which was reported as a drawback by the participants. To guide other team members, they were typically using the door as a reference to give direction in the 360-degree environment. Figure 10 shows two examples of the markup in both BIM and VR platforms. The names of the participants are censored in the VR platform.

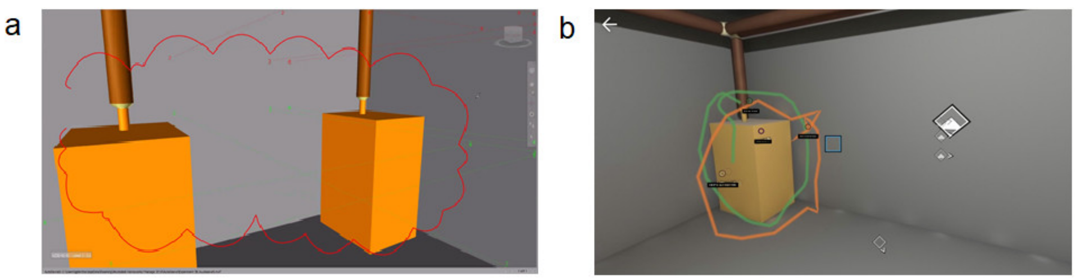

Figure 10. Teams creating markup during meetings in: (**a**) BIM platform; (**b**) VR platform.

4. Discussion

This research study was conducted to study the effects of VR's immersive environment and markup tool capabilities on the team's collaboration efficiency in remote 3D coordination processes. In the asynchronous study we focused on the effects of the VR features on the individuals' understanding of the technical knowledge exchange in a one-by-one communication method. We later studied the effects of VR features on the team's Shared Understanding in a synchronous team interaction. On the individual level, the majority of participants reported having a better understanding of the building system conflicts in immersive VR compared to BIM. They preferred VR's markup in the 360-degree environment compared to BIM's markup with the screenshot of the model to understand the building system conflicts and the proposed resolution. The synchronous study results showed that VR's immersive environment and markup tool capabilities supported team collaboration. First, all teams spent less time in VR to build Shared Understanding of the design alternatives among team members than when using BIM. Group BV3, who proposed the optimal design alternatives for both scenarios, spent significantly less time in the meeting in VR in comparison to the BIM platform. Second, among six meetings conducted in VR, three meetings resulted in correct alternative design, and two meetings had a proposed design very close to the acceptable option. In the BIM platform, only two meetings out of six resulted in the correct alternative design with considerably longer meeting durations. Third, Passive members, on average, shared better understanding of the design alternative with the team in VR. In one group, a Passive member in BIM performed as an Active member in the VR platform. He used the markup tool to communicate the structural constraints and design alternatives while he was misunderstood by other team members in the BIM platform, where he did not share his screen to explain his disciplinary constraints. Fourth, participants reported VR's immersive environment as a feature missing in the BIM platform that supported their team collaboration. Group BV2, in particular, did not use the markup tool in VR and could communicate the design alternative effectively by asking members to use their imagination. The observational study showed that efficient team collaboration in VR required the members to properly guide each other in the 360-degree environment; otherwise, some members could not follow the conversations. In teams where most of the members shared the same understanding of the team decision, the markup creators were asking the team to first look at an object in the space like the door, and then by using the markup tool, they were guiding the team members in the 360-degree environment. Consequently, BIM's shared screen feature was preferred by Active members since it ensured them that all members were looking in the same direction in the model. Overall, this research study showed promising results for more efficient technical collaboration among AEC professionals using immersive VR enabled with markup tools in comparison to the current BIM-based industry practices in explaining disciplinary constraints and technical analysis and brainstorming to find solutions and make decisions in remote 3D coordination processes.

4.1. Limitations

The controlled experiments in this study were conducted with a 3DOF VR that required the research team to set up the BIM platform in a way that it provided the same 3DOF experience in VR as for the BIM users. In the industry, AEC professionals explore models with 6DOF using BIM software navigation tools like Walk. The scenarios were designed in a way that they could be compared in a controlled experiment and were not real-world problems. Furthermore, the participants were graduate students with a few years of industry experience and exposure to BIM practices. This required the research team to simplify the disciplinary knowledge and define it for each role. While participants engaged in this study exercise, other settings should be explored to further validate these findings.

4.2. Future Studies

A similar controlled study with 6DOF VR is recommended to allow the team members to walk inside the model and experience it the way models are explored with BIM. In 3DOF VR, markup is created on a 360-degree static photo that allows users to see the annotation from different rotational angles while fixed in one location. In 6DOF VR, a 3D markup would be seen differently from different locations and angles. A study can be designed to investigate the advantages and disadvantages of creating 3D markup in 6DOF VR. Future experiments are also recommended to study if the avatars in 6DOF VR can resolve the team members' disorientation problem in 3DOF VR by guiding them in the virtual environment with body language. Future research studies need to be conducted with AEC industry professionals to explore how markup enabled immersive VR can be used in day-to-day 3D coordination practices.

Author Contributions: Conceptualization, B.A.A. and C.S.D.; Data curation, B.A.A.; Formal analysis, B.A.A.; Investigation, B.A.A.; Methodology, B.A.A. and C.S.D.; Project administration, B.A.A.; Resources, C.S.D.; Supervision, C.S.D.; Validation, B.A.A.; Visualization, B.A.A.; Writing—original draft, B.A.A.; Writing—review & editing, C.S.D. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: The University of Washington's Human Subject Division issued the IRB approval #STUDY00006457 for conducting this research study.

Data Availability Statement: The transcripts of the meetings and participants' responses to the questionnaires are confidential in nature and may only be provided after anonymizing by the corresponding author upon reasonable request. The BIM model used in the first experiment was provided by Skanska, the Burke Museum project's general contractor. Direct requests for receiving the model may be made to Skanska or to the corresponding author to coordinate. The BIM model used for the second experiment will be provided upon request by the corresponding author.

Acknowledgments: Special thanks to Thomas A. Furness III at the University of Washington for his valuable input in the design of the study. Many thanks to the University of Washington's College of Built Environment's Computing team for their technical support.

Conflicts of Interest: This research study was conducted in collaboration with a start-up company that is no longer in business, and the mobile application used for this study is no longer in the market. The second author was the Strategic Advisor of the company with a small number of shares. The name of the company and the mobile application are not provided in this manuscript.

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