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IMMERSIVE VIRTUAL REALITY MOCKUP VERSUS PHYSICAL MOCKUP: EFFECTS OF IMMERSIVE VIRTUAL ENVIRONMENT ON AECO TEAM DECISION-MAKING PROCESS

Bita Astaneh Asl[1] and Carrie Sturts Dossick[2]

ABSTRACT

This paper presents the results from an academic-industry partnership where a team of university researchers and architecture, engineering, and construction industry (AEC) professionals compared a physical mockup to an immersive virtual reality (VR) environment. The goals of this research were to understand how and in what ways VR can replace the use of physical mockups. The study included an experiment where two groups of AEC professionals reviewed a physical mockup and a VR mockup of the same hotel room layout. Group members were asked first to evaluate each mockup from the owner's standpoint as hotel guests and housekeepers, and then suggest design changes based on their professional expertise individually. The groups were then asked to discuss the design together and make a team decision. At the end of the experiment, participants reflected on how the VR mockup did or did not meet their needs in reviewing the room design. The findings from this study show that VR cannot yet fully replace physical mockups due to the user dimension perception, lack of touch sense, unrealistic simulation in VR, and the need for physical samples. However, participants reported VR could be a cost-efficient tool to look at design options and layout in the early design phase and get feedback from the project team and end-users before the construction of the physical mockup to save potential time and money in rework. They also suggested using VR for visualization of the conflicts between different building systems in 3D coordination process.

KEYWORDS

Immersive virtual reality, physical mockup, design review, dimension perception, 6DOF HMD, collaboration.

1 School of Engineering, California State University, East Bay, bita.astanehasl@csueastbay.edu

2 Department of Construction Management, University of Washington, Seattle, cdossick@uw.edu

INTRODUCTION

There has been a renewed interest in Virtual Reality (VR) tools in recent years due to new technology developments. New viewers, platforms, and cameras are emerging on the market that push the Virtual Design and Construction (VDC) teams in the architecture, engineering, and construction (AEC) industry into testing these new systems. These professionals are fluent in creating Building Information Models (BIMs) for design and construction uses. The new emerging technologies present questions about how VR can support design and construction. While BIMs are displayed as 3D models of designs on 2D display systems for teams of AEC professionals and their clients to study and explore, VR introduces a new display system where the user is immersed in the world. VR is a computer-aided technology that simulates the reality human beings experience in the real world. While the 2D display systems allow for first-person navigation of the model, the first person has a limited perspective where it is difficult to gauge dimensions in space. VR provides a significantly better dimension perception of 3D models compared to desktop platforms (Paes et al. 2017). It brings up questions on whether VR can replicate the finished designs and eliminate the need for full-size physical mockups that are built for evaluation of proposed design and construction by the AEC and owner (AECO) teams.

This research study was developed based on an academic-industry collaboration between the research team at the University of Washington (UW) and three architectural, structural engineering, and general contracting firms to compare the immersive VR mockup with the physical mockup. The study was conducted on a large hotel project with over one million square feet of space for guests. In this project, similar hotel room types were designed to be built in large quantities. The AECO project team was finalizing the room design by reviewing the physical mockup before they were constructed in the building. The UW team and industry partners were interested in studying to what extent the project team can rely on the VR mockup to finalize the design of hotel rooms and whether it can eliminate the requirement for the contractor to build the physical mockup.

BACKGROUND

Different types of mockups are built for specific purposes at various phases of the project. Physical mockups are typically full-sized representations of the proposed construction, built for evaluation of design and construction. They are usually constructed for complex and unique structures, or costly or highly repeatable units of the building. Visual mockups are usually requested by the owner to support making decisions on design options. Performance mockups are built for testing the integration of assemblies and engineering performance. Prototype mockups are made for developing and testing custom assemblies. Field mockups are on-site mockups constructed adjunct to building prior to installation on building. The in-place mockup is built for installation quality assurance (Maing 2012). In this research study, full-sized physical and visual mockups were examined. The visual mockup was created with immersive VR technology, which is also called a virtual mockup.

VR is a technology that is experienced through the senses (Jerald 2015). It gives the user a sense of being in a virtual world. Immersive VR experience can be created with projective systems or head-mounted displays (HMD). Projective systems project the VR content on large-scale curved screens or sides of a cube. For instance, the Cave Automatic Virtual Environment (CAVE) is a projected system where the virtual world is presented by projecting the virtual model on the ceiling, walls, and floor of the room-sized cube (Cruz et al. 1992). The location of users can be tracked in CAVE, which enables the users to walk around in the virtual environment. Users wear a head-mounted device that allows the system to detect where they are looking and can use a variety of input devices or gestures to transmit commands. The HMD systems are worn on the head and block the users' view of the physical environment. An HMD hardware has two embedded liquid crystal displays (LCD), which present each eye an image from a slightly different angle to mimic human optic function. Two types of HMD hardware are currently available in the market. One type has three degrees of freedom (3DOF), meaning three rotational movements of the head are supported. It allows users to look around in different directions while the virtual viewpoint is fixed. The second type has six degrees of freedom (6DOF), meaning both the head rotational and transitional body movements are tracked. This allows the users to look around in virtual space and walk around to explore the world in the first-person perspective through their own eyes. The 6DOF technology is more expensive than 3DOF and more difficult to get right due to body location traction, and the headset needs to be calibrated to the height of the individual for best results.

Prior research studies find VR a useful tool for design review. A limited number of these studies had conducted experiments to compare immersive virtual mockups with physical mockups, which were all created with projected VR systems and had mainly focused on the end-user experience. Majumdar et al. (2006) conducted an experiment in which judges and attorneys evaluated a virtual mockup of a courthouse with CAVE compared to a physical mockup made up of plywood. The decision-making time in VR was cut to less than fifty percent compared to the physical mockup since VR provided real-time modifications to the design based on the participants' feedback. Maldovan et al. (2006) evaluated a different courthouse in which the owner, end-users, and contractors evaluated a courtroom design both in VR and a plywood mockup. An immersive virtual environment was presented by projecting the model on three large screens. VR enabled the users to virtually sit in different locations of the courtroom to understand the design and sightlines. Participants found VR to be most useful for the evaluation of sightlines, which was the most important aspect of the review. Westerdahl et al. (2006) compared a virtual office building mockup with the completed building from the standpoint of employees. The virtual environment was projected on a concave powerwall, and to achieve the 3D effect, users wore a pair of stereo glasses called Crystal Eye. In this study, participants did not have direct control of the projected VR environment. The results show that the employees found VR a useful tool in understanding the future building compared to the built office building. They reported the furniture and people, static images of staff, as the most important details in VR mockup to form an opinion about the size of rooms. Dunston et al. (2007) conducted a study with CAVE, in which a hospital patient room was evaluated by healthcare personnel. Participants provided positive feedback on the use of VR for design review, which included some of the nurses who had worked in the actual facility from which the VR mockup was created. Another design review of a medical project was evaluated by Wahlstrom et al. (2010). It was conducted with CAVE focused on the experience of nurses and patients in reviewing a hospital patient room. While CAVE was a useful technology to help the end-users understand the design and layout, users had a hard time understanding the sufficiency of the space and room size for assessing precise fittingness. Based on the observational study, the users seemed to evaluate the room on the basis of touch. As a result, the researchers suggested complementing the CAVE experience with an evaluation session where physical objects of the VR mockup are used. Castronovo et al. (2013) compared the design review of VR mockups with two projected systems of CAVE and curved screen. CAVE provided a fully immersive experience where the model was projected on five sides of the cube, and the curved screen provided a semi-immersive experience where the model was projected on three large screens. An experiment was conducted based on a new campus building evaluated by future occupants, owner representatives, architects, and a construction manager. Participants provided positive feedback for both platforms. The research study's primary outcome was that a fully-immersive system was more appropriate for smaller groups that desired a higher level of immersion, and the semi-immersive system with a larger footprint was more suitable for larger groups. Zaker and Coloma (2018) conducted a research study in collaboration with AEC industry partners on a virtual model of an office building with 6DOF HMD. The architectural model was reviewed by the owner and architects, and a federated model of structural, architectural, and MEP systems was reviewed by a BIM modeler and an MEP installer. Participants were both interviewed and surveyed with likert-scale questionnaires. While participants were very satisfied with their VR experience in the study, more than half of them found VR to some extent to be practical in their day-to-day practices, with the rest finding it practical. Some drawbacks reported by some participants were motion sickness, feeling tired after wearing the device and difficulty to move around with the device as well as difficulty with getting used to it. More than half felt comfortable wearing the device. The top three use cases of VR were selected as the presentation to the client, internal design review with colleagues, and collaboration with other project teams. Liu et al. (2020) conducted a research study with various participants in the industry, including owner representatives, end-users, facility managers, architects, engineering, and contractors. VR content was created by projection on large three screens supplemented with 2D visuals like drawings and 3D BIMs. The study found that virtual design review is more effective when VR mockup is supported by other design visualization media.

As the research study developed, the architecture firm expressed specific interest in examining how the users perceive the space in the VR compared to the physical environment since they had observed some differences in dimension perception of the owner representatives exposed to their previous VR mockups to evaluate the architectural design. As an example, they shared their experience of observing some users perceiving the width of the spaces narrower than the actual size. Henry and Furness (1993) conducted an experiment with architects who explored a real museum gallery and compared their experience with exploring the 3D model with monitor and HMD. Participants used a spaceball to move inside the digital model. Two types of HMD hardware were used in this experiment, one without capturing head movement, and another one, which could capture rotational head movements from side to side. The experiment results showed that participants underestimated the spatial dimensions in all three digital platforms. Architects who used the HMD hardware with tracked condition reported the most underestimated spatial dimensions, which were as much as 20% for horizontal dimension. Renner et al. (2003) did a comprehensive overview of the literature on dimension perception in VR created by both projected systems and HMD, and reported that users generally underestimate virtual dimensions by 26%. The important factors affecting the dimension perception were categorized under four groups of measurement methods, technical factors, compositional factors, and human factors. For measurement methods, blind walking with HMD was recommended. In the blind walking method, the user views the distance to the target object and then performs some kind of action, like walking towards it to reach in personal space. The recommendations for technical setup to facilitate dimension perception include providing binocular disparity that can be available in HMD where different images are projected on each eye, use of high-quality graphics, display of regularly structured ground texture, and enhance the user’s sense of presence in VR. It was suggested that adding pictorial depth cues improves distance perception. Adding an avatar in case the user feels it's his or her body could correct distance estimation. Human factors affecting the dimension perception might be related to user’s sense of presence, experience with VR, or visual ability. A study on dimension perception with 3DOF HMD hardware was conducted by Loyola (2018) with a focus on the effects of compositional factors on dimension perception that compared real and virtual rooms with different visual cues. The first case was an empty room. The second case had a few boxes and a window as visual cues, and texture was defined for the materials. The third case was a furnished room with furniture and material texture that had high availability of visual cues. In this study, the egocentric dimension, the distance between a point and the user, and the exocentric dimension, like the room's width and length, were studied. The results showed that participants tended to see the egocentric dimension in the empty room 30% smaller than the actual size on average. This value was 11% for the exocentric dimension. The underestimation of the egocentric dimension reduced to 9% when visual cues were added in the third case. The exocentric dimension stayed at 11%. While the egocentric dimension perception improved in the second case compared to the empty room, it adversely affected the exocentric dimension perception. It was concluded that not providing enough visual cues can deceive the user. It should be noted that the data showed a variety of dimension perceptions where participants perceived dimensions as both larger and smaller than actual. The more visual cues were provided in the model, the better users could estimate the dimension. However, they did not perceive the virtual dimension as the actual size. Dimension perception studies has also been conducted on various VR hardware to evaluate the effects of technical factors on dimension perception. HTC Vive was the HMD hardware used in our study. Research studies conducted with HTC Vive show a wide range of dimension perception accuracy, perceived dimension divided by actual dimension, with average values ranging from 66% (Buck et al. 2018) to 102% (Zhang et al. 2021). Kelly (2022) conducted a meta-analysis of data from 61 research studies across 20 HMD hardware on dimension perception with different measurement methods (e.g. verbal, blind walking, ect.). The study shows Oculus Rift CV1 had the highest dimension perception accuracy with an average value of 86.42%. The second and third highest precision HMDs were HTC Vive and Oculus Rift DK2 with an average perception accuracy of 82.18% and 79.82%, respectively. Feldstein et al. (2020) conducted a literature review on 19 research studies that used blind walking as the method of dimension perception measurement using various HMD hardware. They sorted the data chronologically and found an improvement in dimension perception accuracy in time due to improvements in HMD hardware's technical features.

The research team did not find experimental research studies comparing the physical and virtual mockups using HMD hardware. The dimension perception studies conducted with HMDs showed a wide range of accuracy. Prior research studies on the application of VR for design review were focused on the end-user experience. This motivated the research team to conduct an experiment to compare the physical mockup with the immersive virtual mockup created with 6DOF HMD that involved the AEC professionals in the design review process.

RESEARCH METHOD

The UW research team designed an experiment to compare the immersive VR and physical mockups. The experiment variable was the environment where the physical environment was set as the control platform. The architectural firm owned the VR mockup of the hotel room, and the general contractor had built the physical mockup in a warehouse. The structural engineering firm showed interest in participating in this study to evaluate the VR mockup from the engineering standpoint and support the project team with their expertise in case the team decided to make design changes that could affect the structural design. Questionnaires were designed to capture the effects of the environment on the participants' understanding of the model as well as individual and team decision-making. The experiment was video recorded for observational study purposes.

Participants

The research study participants were volunteer employees from the three AEC industry partners involved in the hotel project. The participants were divided into two diverse groups based on their discipline. Table 1 summarizes the participants in groups of PV and VP. The group naming was based on the platform order the groups experienced in this study where the letter P refers to the physical mockup, and the letter V refers to the virtual mockup. Six architects, four VDC specialists, two project engineers, a superintendent, and two structural engineers participated in this study. The superintendent was assigned to Group PV, and two project engineers were assigned to Group VP, all categorized under the Construction discipline.

Experiment Setup

The experiment was conducted in a warehouse owned by the general contracting firm where the hotel room mockup was located. The mockup was furnished and represented the final design. Figure 1 shows the hotel room's plan. The hotel room had an entrance space with a bathroom on the right side. The bathroom included a glass-doored shower area, a sink with an open shelf beneath the countertop, a full-size mirror on the wall, and a toilet. A sliding door was installed for the bathroom. The entrance area was connected to the sleeping area with a size of about 11 ft x 20 ft. The bed was located in the middle facing a wall-mounted TV with a desk on one side and a shelving cabinet including a lock system and refrigerator on the other side. An open closet was located at the entrance of the sleeping area next to the TV. The window was located at the far end of the room.

An immersive VR mockup of the same hotel room was created by the architects in the gaming engine, Unity. HTC Vive, a 6DOF HMD hardware, was used in this study. The recommendations of Runner et al. (2003) were all followed, with the exception of creating an avatar for the user, by providing high-quality graphics, binocular disparity, regularly structured ground texture as it looked in the physical mockup. The room was fully furnished and provided enough visual cues to better estimate the virtual dimensions per Loyola (2019)'s findings. Users could estimate the dimensions with blind walking due to the 6DOF nature of the hardware used in the study. The VR system was set up in an open space next to the physical mockup. HTC Vive supports movement within a diagonal area of up to 16 ft, which means the maximum recommended navigable space is about 11 ft x 11 ft. The hotel room's width was close to 11 ft; however, the length was larger than the recommended size for HTC Vive. As a result, the VR mockup was divided into three zones, as seen in Figure 2.

Table 1. Research study participants in groups PV and VP

Group PV		**Group VP**	
Discipline	**Number of Participants**	**Discipline**	**Number of Participants**
Architect	3	Architect	3
Structural Engineer	1	Structural Engineer	1
VDC Specialist	2	VDC Specialist	2
Construction	1	Construction	2
	Total: 7 Participants		**Total: 8 Participants**

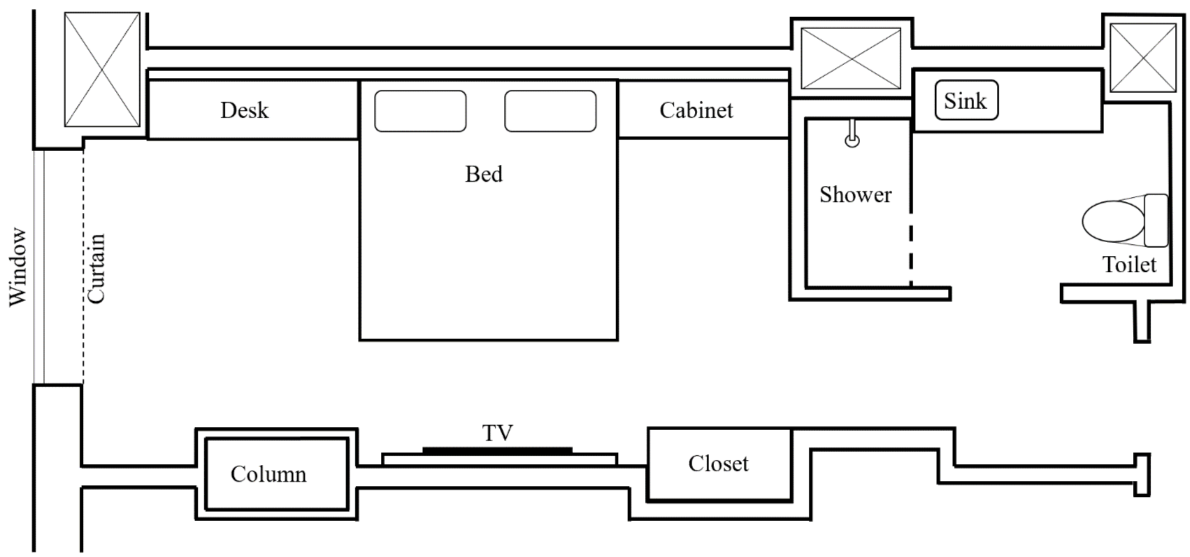

Fig.1. The hotel room's plan

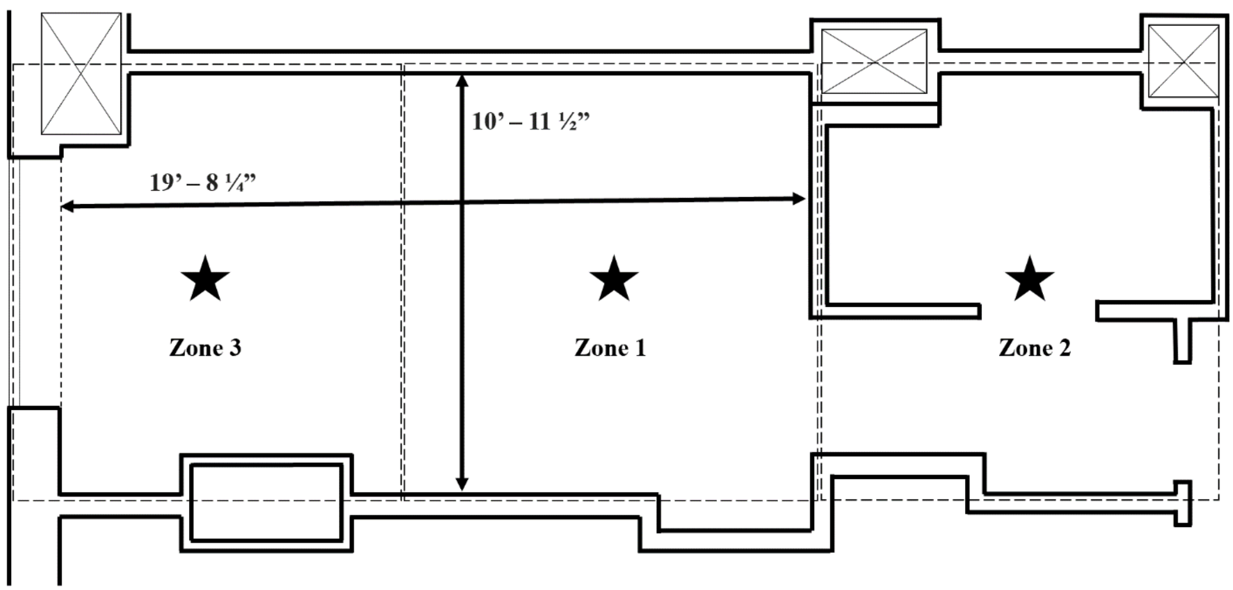

Fig.2. Zones for exploring the model in VR

The VR mockup was set up in a way that the user would enter the environment next to the bed, as shown with a start symbol in Figure 2, and could walk around and explore the room from the sleeping area entrance up to the middle of the bed. To explore beyond Zone 1, the users had to be teleported to other zones, meaning they would immediately find themselves in the middle of a different zone without walking to that location. Figure 3 shows a comparison of the physical and immersive virtual mockups captured from Zone 3.

Questionnaires

In this research study, a personal information questionnaire and two sets of questionnaires A and B were designed. The personal information questionnaire was focused on the participants' backgrounds and previous experiences with BIM and VR. Questionnaire A was designed to capture the participants' experience and their suggestions for the design changes. Questionnaire B was designed to capture the participants' opinions on the comparison of the two mockups. Two Questionnaires A were given to the participants to fill out at the end of their experience in each mockup, and Questionnaire B was provided at the end of the experiment. Since dimension perception could be an important factor affecting the participants' understanding of the design, the UW team added a dimension perception measuring tool to both questionnaires A and B. The focus was on the exocentric dimensions. Participants were given the exact measurements of the room width, length, and height in Questionnaire A, and were asked to answer whether they perceive the dimension in the mockup the same, shorter or longer than the actual size. In Questionnaire B, they were asked to compare the room dimensions in VR and physical mockups. Since no owner representatives participated in this study, the experiment participants were asked to evaluate the hotel room from the standpoints of hotel guests and housekeepers to reflect on the possible owner requests on design changes. They were then asked to reflect on what they would change from their profession's point of view to make a better investment considering the overall building life cycle cost. At the end of the experiment, participants reflected on the features of VR that contributed to their understanding of the design and decision making and the features that were the drawbacks by filling out the Questionnaire B. They evaluated the immersive VR mockup by answering multiple-choice questions with likert-scale options. In these questions, participants were asked to answer the extent to which the VR mockup was helpful to simulate the future hotel room to understand the design and make decisions based on their professional background. Participants were asked to compare the VR mockup to the same model on the laptop's 2D screen. They also reflected on how likely they will consider using VR mockups in the future from the standpoint of the owner to evaluate the design if they don't have the physical mockup. Participants were also asked to suggest which coordination task types will benefit from the use of VR in the project.

Process

The UW research team was responsible for the group facilitation, data collection, and taking notes of their observations during the experiment. Participants were given a folder at the start of the experiment that included the research study description, the personal information questionnaire, two Questionnaires A, and one Questionnaire B. Group PV was assigned to start the experiment from the physical mockup and then move to the open space next to the mockup to experience the immersive VR mockup. On the other hand, Group VP started the experiment from the immersive VR mockup and then switched the platform to the physical mockup. In both the immersive VR and physical environment, the participants were asked first to experience the environment individually. They were then asked to reflect on their experience and explain their individual suggestions for design changes by filling out Questionnaire A.

Fig.3. The hotel room mockup; physical mockup (on the left), and immersive VR mockup (on the right)

After the individual experience, groups discussed the room design as a team and made a team decision on design changes. After the groups made team decisions in both mockups, the participants were asked to fill out Questionnaire B. To capture the individual and group interactions with the environment and record the conversations, one camera was positioned at the corner of the hotel room next to the window in the physical mockup, and another one was located at the open area next to the VR setup.

RESULTS

Based on the personal information questionnaires data, all the participants were familiar with BIM and had used it in their profession. Only one participant did not have any experience with VR, and the rest were previously exposed to the virtual environment. The range of participant age was between 25 and 51 years old. This range was (25,51) for Group PV and (26,51) for Group VP. The average age for both groups was 36 years old. A total of 53% had a master's degree, and the rest of the participants had a bachelor's degree. The results of the observational and questionnaires data analysis are explained as follows.

VR Features Affecting Individual and Team Decisions

Comparing the immersive VR and BIM, all participants reported finding immersive VR environment very helpful to understand the space. Exploring the model from the standpoint of the first person in a realistic model, immersed in the environment surrounded by the building objects, and being able to look at the model from different angles like exploring it while bending down were the reasons given by the participants to find the immersive VR a more useful tool over BIM to understand the model. While VR gave the participants a better understanding of the space in comparison to BIM where 3D models are projected on 2D screens, some VR features were adversely affecting the decision-making process in comparison to the physical mockup. The results show that users had different dimension perception of the immersive virtual environment in comparison to the physical mockup, and features like lack of touch and unrealistic simulation affected their decision-making process. The research study also showed that VR does not eliminate the need for physical samples. These VR features are explained as follows.

Dimension Perception

In this experiment, only one participant reported perceiving the dimensions in both immersive virtual and physical environments the same. This participant was a member of the general contracting firm' VDC team, who worked with VR on a daily basis. Other participants experienced differences in perceiving dimensions. Table 2.2 summarizes the participant's report of their dimension perception by comparing the virtual sleep area dimensions to the actual sizes in the physical mockup.

More than half of the participants, 53%, reported perceiving the sleeping area's width narrower than the physical mockup. Among the rest, 27% perceived it the same as the actual dimension, and only 20% perceived it wider. The results confirmed the architectural firm's previous experience of witnessing the majority of owner representatives perceiving narrower width of the space in comparison to the actual width size. With regards to length, only 20% reported perceiving the same length in both platforms. The rest of the participants were equally grouped in two, half perceived the dimension bigger, and half perceived it smaller than the actual size. Although the VR headset was calibrated to height, tall participants felt short in this experiment. Among participants who perceived the room height dimension the same as the mockup, some reported perceiving the height of the bathroom countertop higher than the physical mockup.

Table 2. Participants' dimension perception

	Group	$D_{Virtual} < D_{Actual}$		$D_{Virtual} = D_{Actual}$		$D_{Virtual} > D_{Actual}$	
		Participant #	Total (%)	Participant #	Total (%)	Participant #	Total (%)
Width	PV	3	53%	2	27%	2	20%
	VP	5		2		1	
Length	PV	2	40%	1	20%	3	40%
	VP	3		2		3	
Height	PV	0	0%	3	40%	4	60%
	VP	0		3		5	

One participant who perceived all virtual sleeping area dimensions the same as the physical mockup reported seeing the virtual furniture larger than the actual ones. Several participants reported having a hard time understanding the depth. For example, some had perceived the countertop width in the bathroom smaller than the actual size.

Since each participant had a different understanding of the dimensions in the immersive VR mockup, it affected the team decision. For instance, Group VP, who started the experiment from the immersive virtual environment, discussed widening the room width to provide more space for the visitors to walk around the bed with luggage and for the housekeepers to clean the area. Later in the physical mockup, these participants realized the actual width in the physical mockup was wider than what they have perceived in the immersive VR mockup and reported to the team the reason they believed the width in the virtual mockup seemed to be not enough for them. While Group PV had a conversation about the large size of the TV and discussed installing a smaller one while exploring the room in the physical mockup, they reported seeing the TV smaller than the actual size in the immersive VR mockup.

Lack of touch sense

In current VR practices in the AEC industry, the only simulated sense is typically sight. The experiment participants experienced an environment that was lacking the simulation of four other senses. Potentially the senses of taste and smell did not affect the decision-making process, and evaluating the acoustic features of the room was not of interest in this study. The results of the experiment show that the touch sense has an important role in understanding the immersive virtual environment. The participants were able to walk through the virtual objects like bed and walls without hitting them. As a result, when they were exploring the room to understand if they have enough space in the room to move luggage or bend for cleaning the space, they were not aware if some parts of their body were beyond the wall boundary or if they could hit any furniture like wall-mounted TV in the room. Based on the observational study, participants were trying to touch the objects by hand while they were immersed in the VR mockup. They reported having a hard time understanding the surfaces because of the lack of touch. Group VP found more spaces that needed to be cleaned in the physical mockup. As an example, one participant touched the bases of the bed and closet to understand the gap beneath them. Participants also wanted to open doors and try out other moving features in the physical mockup. Group VP found that the sliding door seemed flimsy and predicted it would break easily. For both groups, touch was an important element in understanding the space and design choices.

Unrealistic simulation

Besides the lack of touch sense simulation, participants also reported some unrealistic simulation features in VR that were affecting their understanding of the environment. Participants were placed next to the bed at the beginning of the virtual experience and were limited to walk in an area of about 11x11 ft due to the HTC Vive suggested navigable area. To walk beyond the zones, participants were teleported. Exploring the room in the immersive VR mockup did not have the same flow as in the physical mockup where the participant walked through the hotel room, passed the entrance area where the bathroom was located on the right, and then walked across the room towards the wall with a window. In VR, participants found the disconnection between the teleportation and the limitation for exploring the model beyond the boundaries as factors affecting their understanding of the space. Another feature was the incapability to see their bodies. One participant suggested simulating the controllers, which would give them an idea of where their hands are. This participant suggested that it would help them understand the height of objects in the rooms. Based on another input from a participant, controllers could also be used as a measurement scale to understand the dimensions, especially the depth. It was also mentioned that it is hard to imagine carrying luggage in the virtual space. This lack of self-representation was affecting their decision in evaluating if enough space is available for carrying luggage in the room and bending down or vacuuming the area during housekeeping. Another feature reported by a few participants was the unrealistic mirror simulation. Mirrors in the virtual space were not functioning like real mirrors to reflect the light and show the background space while standing in front of them. They reported this feature as a drawback to understand the space. Participants also were not able to see themselves in the mirror, which felt weird to them.

Need for Physical Sample

Based on the feedback from the participants, VR was not able to eliminate the need for physical samples both small samples (to understand the material, texture, etc.) as well as full-scale samples (such as built-in-closet, and bathroom doors), to help the participants in making a decision on design options. Group PV had decided to remove the sliding bathroom door. They moved the door back and forth to understand the functionality. The door was causing some noise. The team also discussed the door noise that could wake up the second guest in room at night. The superintendent also checked the door track and supported the decision of door removal due to the maintenance problem. Participants had a hard time understanding the materials and the final quality of the furniture. It was impossible to figure out the quality of the material and surface textures in VR. In the physical mockup, one participant from Group PV touched the surfaces to understand how easily the surface material could catch the dust to decide on the frequency of the dust cleaning by housekeepers. Questions like how the seams would look or how durable the furniture would be were unanswered in VR. As an example, they were not sure if the open closet shelf was well made enough to put heavy luggage on. Participants in both groups concluded that VR is useful in early phases of design when designers and owners' representatives are making decisions, but for final product choices, the physical mockups were still invaluable to test the materials and hardware.

Immersive VR Mockup Evaluation

Participants were also asked to evaluate the VR mockup from the owner and their profession standpoint by answering questions with likert-scale options. The data showed a correlation between age and prior experience that, on average, the higher the age, the more prior experience participants had with VR. Participants in the higher ranges of age had managemental job responsibilities involved with project decision-making processes. These participants tend to have more positive feedback on reviewing the virtual mockup both from the standpoint of the owner and their own profession on average.

Owner Perspective

Participants were asked first to evaluate the mockups from the standpoint of an owner. In Questionnaire B, they indicated how likely they would use immersive VR in the future to assess a mockup as a hotel guest and housekeeper based. Table 3 summarizes the responses for each group and as a total based on the likert-scale values. Group VP who started the experiment from VR were more satisfied with their experience in VR than Group PV. Based on the participant reflections in Questionnaire B and discussions after the experiment, it was interpreted that since Group VP followed the same sequence practiced in the industry, they did not have much expectation from the immersive VR mockup, which resulted in supporting this platform more than Group PV. On the other hand, since Group PV saw the actual mockup in the physical environment, they were able to evaluate the virtual mockup more critically and reflect on to what extent it replicates the physical mockup. While Group PV's response was neutral on average, Group VP showed more likelihood to use VR in the future for evaluating the mockup as end-users.

Table 3. Likelihood of using immersive VR in the future

Role	Group	Group Ave. (Answers)	Total Ave.
Guest	PV	2.9 (1,2,3,3,3,3,5)	2.4
	VP	1.9 (1,1,1,1,1,2,4,4)	
Housekeeper	PV	3 (2,2,2,3,4,4,4)	2.2
	VP	1.4 (1,1,1,1,1,1,2,3)	

Very Likely = 1, Likely = 2, Neutrual = 3, Unlikely = 4, Very Unlikely = 5

AEC Professional Perspective

Participants' responses to what extent they found VR mockup a helpful tool to (1) understand the design and (2) make decisions based on their AEC professional background if they did not have the physical mockup are summarized in Table 4 based on the likert-scale values. The structural engineers were the only participants who reported the same in both mockups. On average, the architects had relatively close opinions regarding the use of immersive VR for their profession. The responses of the construction team and VDC specialists from the general contracting firm showed the same patterns observed for the mockup evaluation from the owner's perspective. Group VP was more satisfied with the VR experience.

Table 4. Evaluation of immersive VR mockup by disciplines

Discipline	Group	Understand Design		Make Decision	
		Group Ave. (Answers)	Total Ave.	Group Ave. (Answers)	Total Ave.
Architecture	PV	2.7 (2,2,4)	3	4 (4,4,4)	4
	VP	3.3 (2,4,4)		4 (2,5,5)	
Structural Eng.	PV	2 (2)	2	1 (1)	1
	VP	2 (2)		1 (1)	
Construction	PV	3 (3)	2.3	3 (3)	2.7
	VP	2 (2,2)		2.5 (2,3)	
VDC	PV	3 (3,3)	2	2 (1,3)	1.5
	VP	1 (1,1)		1 (1,1)	

Completely Helpful = 1, Fairly Helpful = 2, Somewhat Helpful = 3, A Little Helpful = 4, Not Helpful at All = 5

Among the disciplines, architects were the most unsatisfied participants with regards to using VR mockup for both understanding the model and making decisions. Dimension perception and spatial cognition are critical factors for architects to understand the design and make architectural design decisions. They reported finding VR a useful tool for early design studies to evaluate conceptual ideas and layout and a cost-efficient way of looking at design options without spending time and money on the physical mockup. VR would give them the ability to quickly evaluate different design options while having a better understanding of the space in the immersive virtual environment compared to exploring the 3D model on a 2D screen. However, they mentioned that they would require the physical mockup for the final sign off. The structural engineering firm members were the most satisfied participants due to their reduced concern to understand the dimensions and space. They reported finding VR a useful tool for large-scale structural systems, evaluating different structural system options also known as ABC studies, and visualizing clashes. Clash is referred to the conflict between building systems like MEP and structural. The superintendent was the only member in the construction discipline in Group VP. He reported the lack of physical samples as a drawback in evaluating the design. He also had a hard time understanding the digital model in VR. The two project engineers in Group PV were both very satisfied with the VR experience. The VDC group is mainly involved with virtual construction processes, and VR mockups could be a more useful tool for them. As a result, their response, on average, support the use of VR. The general contracting team suggested using VR mockup to get feedback from the project team before building the physical mockup, which could save time and money in rework. They would need to build the physical mockup for both the owner and designer team's approval and for evaluating construction details. They also envisioned VR to be a useful tool for MEP coordination, which the structural engineering team suggested as well.

CONCLUSION

Both groups in this experiment confirmed that being immersed in the virtual environment gave them a better understanding of the space in comparison to the 3D model presented on a 2D screen. However, they concluded that virtual models could not replace physical mockups due to the limitations in today's technology and the need for physical samples. The main reported drawback of using VR was the dimension perception, which prevented the teams from making decisions on design options where dimension mattered. For instance, VR mockup was supported the least by the architects whose work highly depends on spatial perception. Lack of awareness of the user's body in the virtual space in relation to the virtual objects adversely affected the user's understanding of the VR mockup, which could be improved by adding an avatar and touch sense. It was concluded that VR could be a useful tool for the design review process in the early design phase and MEP coordination to visualize the clashes between building systems in the pre-construction and construction phases.

The limitations of this study relate to the nature of the quasi-experimental design as it was conducted in situ with a real design and construction team who were evaluating the project during the construction phase of the project. Consequently, the designers and builders came with their own agenda for design review and approval. The research team were able to design the questionnaire, but had limited ability to impact the set up for the study in terms of the types of design questions the participants were asking themselves and each other. We did ask them to walk through the physical and virtual mockups in two groups, alternating which they started with and thereby set up the two groups with the physical mockup as a control. Consequently, the research findings in this study are bounded by the context of what types of design decisions the team was making in real time on a real project—the final approval of the room layout and material selection.

FUTURE STUDIES

One of the main outcomes of this research study was an understanding of which VR features could affect the AEC team decision-making process. The VR HMDs currently available in the market tend to provide underestimated virtual dimension perception on average (Kelly 2022). They also have limitations in terms of the navigable space. This resulted in an unrealistic simulation in this study since the participants did not explore the VR mockup in the same way as a physical mockup. As the technology evolves, there is a need to conduct a study with a high dimension perception accuracy hardware that does not restrict the navigation area. Touch sense is another feature that can be added to VR simulation.. Future studies can be conducted with haptic gloves and jackets to test if they improve the understanding of the spatial dimensions. Nevertheless, if space is not a concern for the project teams, the VR content can be evaluated by combining it with the physical environment to simulate the touch sense. For example, in this project, cardboard could be used to demonstrate the wall, bed, and desk boundaries to help the participants understand the space. Adding an avatar is recommended to support user's self-awareness in the environment in these studies. Experiment participants suggested other potential VR use cases that could be considered to evaluate in the future. One of them was using VR to visualize and review clashes in MEP coordination. A future study can be conducted to evaluate the efficiency of using VR for the MEP coordination process compared to the current BIM-based practices. Since the physical mockup was already built in this study and it was representing the final finishes, the architectural design was mainly discussed within the groups. A future research project can be designed for evaluating the decision-making process of the general contractor and subcontractors during the construction phase of the physical mockup and compare it to the process in the immersive virtual environment. This can give a better understanding of how construction professionals would find the VR beneficial for construction coordination.

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