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Birt, James R.; Vasilevski, Nikolche

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Comparison of Single and Multiuser Immersive Mobile Virtual Reality Usability in Construction Education

James Birt[*] and Nikolche Vasilevski
Faculty of Society and Design, Bond University, Australia // jbirt@bond.edu.au // nvasilev@bond.edu.au
[*]Corresponding author

ABSTRACT: Immersive virtual reality (IVR) and mobile technologies have been identified as important in reimaging information delivery and pedagogy. This, coupled with evolving research in single (SUVR) and multiuser (MUVR) IVR environments, may enhance educational practice. However, there is limited research on the impact of such technologies on the learners' experience in authentic learning environments, such as building information modeling in architecture, engineering, and construction (AEC) workflows. This paper addresses this through a study of forty-eight participants recruited from a postgraduate construction course at an Australian University to answer a research question on how mobile MUVR is more useable than mobile SUVR when experiencing building information models. A within-subjects' experiment was performed using a mixed-methods approach assessing participant mobile IVR Usability on a 5-point Likert scale across four constructs and analysis of reflective sentiment and essays. The results show that when the participants moved from SUVR to MUVR, this significantly increased the overall perceived mobile IVR Usability. Combined with the qualitative analysis, these results suggest that MUVR influences mobile IVR Usability and an increase in learner experience. This study can be used as a launchpad for future research that will explore the causes of the evolution of the enhancement that MUVR provides, expanding beyond the scope of AEC education and industries.

Keywords: Virtual reality, Mobile, Multiuser, Learning experience, Virtual reality usability

1. Introduction

Building Information Modelling (BIM) is a new technique being used in the architecture, engineering, and construction (AEC) industry to assist with stakeholder communication, phase scheduling, and design error clash detection (Chan, Ma, Yi, Zhou, & Xiong, 2018). Used throughout the whole building lifecycle, BIM enables advanced forms of interactive visualization through object-related quantitative and qualitative data and visual 3D models (Santos, Costa, & Grilo, 2017). This combination of information and spatial modelling enables optimized workflows and communication that supports the critical success factors (Antwi-Afari, Li, Pärn, & Edwards, 2018) and ever-changing AEC industry compliance (Chan et al., 2018). With the data in AEC projects growing in scale and complexity (Tang, Shelden, Eastman, Pishdad-Bozorgi, & Gao, 2019) there has been a rapid shift in AEC education to integrate BIM into course content leading to integration difficulties (Puolitaival & Forsythe, 2016).

Immersive Virtual Reality (IVR) (Parong & Mayer, 2018; Radianti, Majchrzak, Fromm, & Wohlgenannt, 2020) and the subset of mobile IVR (Ladendorf, Schneider, & Xie, 2019; Olmos, Cavalcanti, Soler, Contero, & Alcañiz, 2018) has been identified as emerging technologies for reimagining education delivery. Coupled with evolving research in multiuser IVR environments (Buck, Rieser, Narasimham, & Bodenheimer, 2019), mobile IVR may enhance learning in spatial disciplines such as AEC education (Birt & Cowling, 2018; Vasilevski & Birt, 2020). However, there is limited empirical research on the usability impact of such methods on the learners' experience.

This paper addresses this through a study of forty-eight participants recruited from a postgraduate construction course at an Australian Higher Education institution. Using a mix of quantitative and qualitative data, participants answered the research question: "How is mobile MUVR more useable than mobile SUVR when experiencing building information models?"

2. Background

Unifying learner skills within professional real-world environments is difficult and complex (Herrington, Reeves, & Oliver, 2014). This is due to a combination of factors such as safety concerns, staffing costs, educating on non-existent environments, liability issues, repeatable experiences, and situated contextual feedback. With AEC projects growing in scale and complexity, there has been a rapid shift in AEC education to integrate authentic industry methods such as BIM into courses, leading to pedagogical integration difficulties.

Puolitaival and Forsythe (2016) noted that most AEC courses use traditional methods such as plan drawings to teach integrated BIM. However, urgent reform is required to embed emerging technologies with collaborative experientially driven approaches to improve authentic learning and industry readiness of learners.

Schott and Marshall (2018) recognize that we best understand experiential education as philosophy, which accepts the idea that learners need to interact with the world to comprehend it. Therefore, if cognitive immersive learning environments are achievable using technology which the visualization and simulation literature suggests (Bower, Lee, & Dalgarno, 2017; Dalgarno & Lee, 2010; Fowler, 2015; Reisoğlu, Topu, Yılmaz, Karakuş Yılmaz, & Göktaş, 2017), then the challenge is achieving alternatives to situated real-world learning through a combination of task design and interactive, immersive environments.

Increasingly IVR has been shown to assist in both industry (Slater & Sanchez-Vives, 2016) and educational (Jensen & Konradsen, 2018) settings. Radianti et al. (2020) published a systematic review of IVR and the pedagogical theories, methods, and domains in which IVR has been embedded in higher education. The authors mapped IVR technology into three domains: (i) mobile VR (Samsung Gear VR, Oculus Go/Quest), (ii) high-end heads mounted displays (HMD) (Oculus Rift, HTC VIVE) and, (iii) enhanced VR (often referred to as mixed reality using haptics and physical world data). It is noted that other systems such as 2D monitors, CAVEs, and similar are classified as non-immersive VR.

According to Radianti et al. (2020) the characteristics of IVR and learning are one of interactivity, presence, immersion, and the interplay of technical attributes such as graphical quality, framerate, and field of view on the individual sense of awareness associated to their personality traits. The authors noted that immersion is the most subjective of the characteristics. Slater and Sanchez-Vives (2016) view the discussion of immersion exclusively related to the IVR system's technical affordances and that immersion may give rise to subjectivity in users and is, therefore, a subjective correlation to presence. That is, if the participants perceive the use of their body within the IVR in a more natural way, then the body's perceptual system is perceived as being there. Johnson-Glenberg (2018) concludes that full-body movement and gestures provide for even more creative actions and learning in 3D with higher presence correlating with higher embodiment levels. This is further examined in their later work, where VR platform choice affects embodiment and learning (Johnson-Glenberg et al., 2020).

Dalgarno and Lee (2010) highlight the impact of immersion and fidelity on the participants' higher active learning function showing that as immersion increases, so does the learning. Fowler (2015) argues that immersion may emerge as a product of the complex interactions within the environment. Bailenson (2018) notes that the interactivity aspects of VR offer tremendous learning opportunities. The connection between immersion and engagement within IVR has been researched by a number of researchers (Allcoat & von Mühlenen, 2018; Hudson, Matson-Barkat, Pallamin, & Jegou, 2019). Huang, Backman, Backman, McGuire, and Moore (2019) noted that "virtual environments have the potential as an educational platform for real-world simulations, professional training, synchronous interaction, and global collaboration to provide interactive and immersive learning experiences and to enhance learner engagement."

Parong and Mayer (2018) identify IVR potential for engagement but cautioned on the immersive medium, as IVR may cause learners to be less reflective and that the VR may be better as a pre-lesson to spark interest, and then learning is formed around conventional collaboration. This is further examined by Bower et al. (2017) by exploring the importance of collaborative participant discussion (communication) and interaction. An essential question in understanding how to develop and build collaborative or multiuser IVR recognizes how people perform actions together, and the impact of social dynamics and affordance behavior is often studied through virtual avatars (Buck et al., 2019).

There is much literature on the use of virtual avatars for education (Dickey, 2005; Hew & Cheung, 2010; Mikropoulos & Natsis, 2011; Reisoğlu et al., 2017) and the impact of physical avatar characteristics on the participants deeper immersion and emotional satisfaction within IVR (Steed, Pan, Zisch, & Steptoe, 2016; Waltemate, Gall, Roth, Botsch, & Latoschik, 2018). The avatar's degree of personalization, realism, and graphical fidelity is significantly related to ownership, presence, and agency in immersive virtual environments (Waltemate et al., 2018). It has also been shown that avatar mediated communication has clear correlations to the social presence (Oh, Bailenson, & Welch, 2018). However, there are concerns about the impact that users' avatars have on others (Turkay & Kinzer, 2014) with deidentification (Merola & Peña, 2009) and motion control (Heidicker, Langbehn, & Steinicke, 2017) being essential considerations, especially in social, collaborative VR.

Heidicker et al. (2017) found that presence, social presence, and cognitive load are influenced by the avatars' body representation with full human representations increasing sense of presence. The degree of avatar mapping to users’ movements increased the feeling of co-presence and behavioral interdependence. Waltemate et al. (2018) also found that the degree of HMD immersion had significant correlation effects in participant agency and feeling of presence.

The focus of this study is on mobile solutions. Current smartphone HMD technology that enables mobile IVR is limited in immersing a user completely in computer-mediated reality but does enable everyone to experience IVR (Ladendorf et al., 2019; Radianti et al., 2020). Papachristos, Vrellis, and Mikropoulos (2017) compared high-end HMD with mobile VR and concluded that mobile-based systems could provide acceptable immersion and contribute to the pedagogy. This is reiterated by Lai et al. (2019) and Olmos et al. (2018) with caution around graphical techniques, communication via audio, and a lack of gesture via reverse kinematics in mobile avatar visualization.

Birt and Cowling (2018) showed that emerging technologies using evolving experiential delivery using mobile devices and IVR show positive usability results in communicating design models across single user implementations. Vasilevski and Birt (2020) extended this research and explored a qualitative thematic analysis approach using assessment of learner reflections of mobile multiuser IVR. However, both stopped short of presenting quantitative assessment and correlation data of IVR usability and experience. This paper addresses this through a mix of quantitative and qualitative data.

3. Method

As noted in the literature review, unifying learner skills within professional real-world environments is difficult, especially when the authentic environments are immersive, complex, and collaborative. This study involves delivering a learning lesson focusing on building space and construction by integrating a BIM model delivered through single-user and multiuser mobile IVR.

3.1. Simulation design

A BIM model illustrated in Figure 1 showing site planning, floor plan, elevations, and sections was developed in Autodesk REVIT 2017.

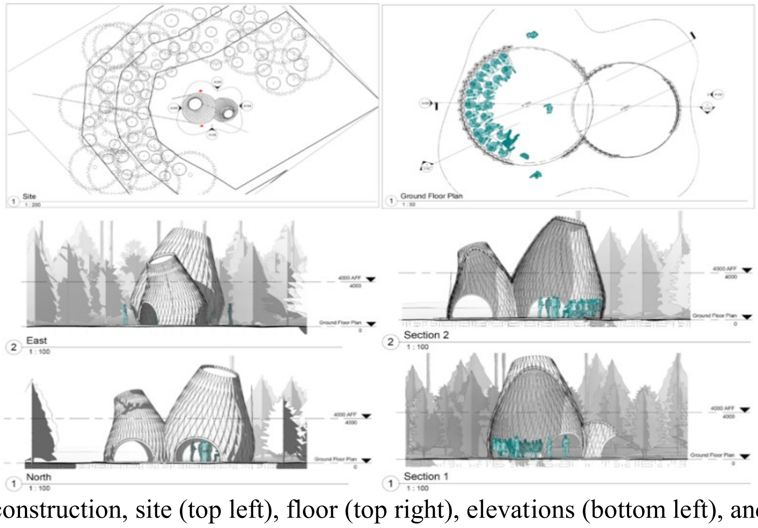

Figure 1. Model construction, site (top left), floor (top right), elevations (bottom left), and sections (bottom right)

The model was revised several times through consultation with the authors, course convener, and architectural designer. Using the developed BIM visualization, the lead author translated the model into mobile IVR using the game engine Unity and the Samsung Gear VR navigation plugin inbuilt into Unity. Model materials and lighting were constructed in line with the BIM model. However, due to mobile device performance constraints, realism was unfortunately reduced, as illustrated in Figure 2 with the BIM renders shown on the left and mobile IVR on the right. The visualization allows for observation of the BIM model over a simulated 24-hour transition simulating the day-night lighting change.

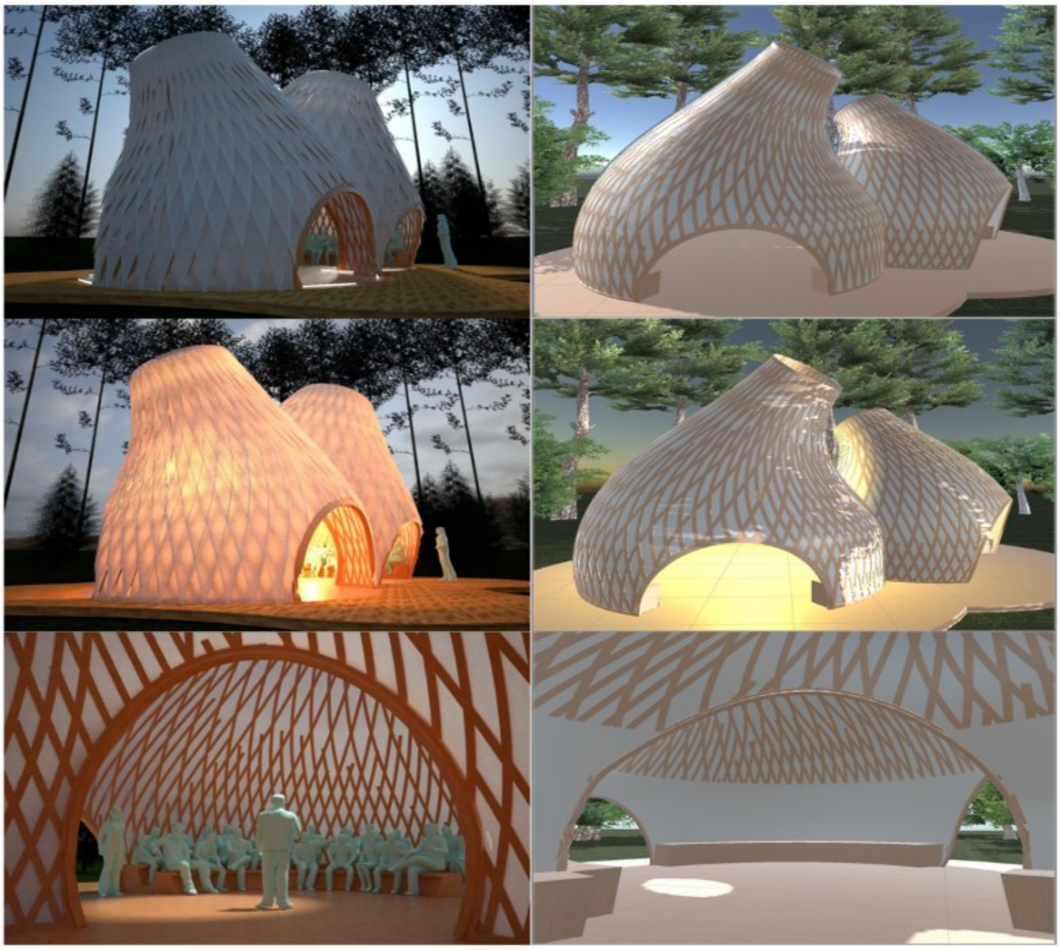

Figure 2. Rendered BIM (left), Unity IVR (right) highlighting mobile visualization compromises

The avatar was developed in two versions, see Figure 3, one with a head (used for the multiuser interaction), and one without (participant self-perspective).

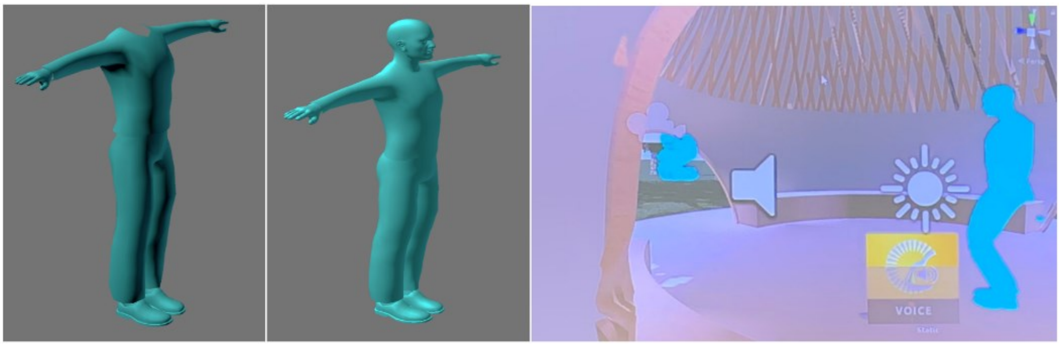

Figure 3. Constructed avatar showing self-view (without head), peer-view (with head), and visualization.

The avatar was built in line with Heidicker et al. (2017) that highlighted the importance of animation and user mapped motion control on the presence and behavioral interdependence. Although the authors understand the significance of avatar personalization, realism, and graphical fidelity (Steed et al., 2016; Waltemate et al., 2018), the overheads of development for a mobile IVR solution is too high. Therefore, a humanoid avatar was developed that identified the importance of complete body representations. The avatar was de-identified and colorized light blue to reduce participant impact effects (Merola & Peña, 2009; Turkay & Kinzer, 2014) but it is noted that the representation is of a male avatar, which represents a limitation of the research. The constructed MUVR environment included multiuser participant visualization of avatars and voice communication in line with IVR development (Bailenson, 2018; Dalgarno & Lee, 2010; Hew & Cheung, 2010; Reisoğlu et al., 2017). The device networking, multiple avatar handling, and voice chat were enabled through the Photon Networking version 1 (see https://www.photonengine.com/pun) plugin for Unity. The multiuser IVR environment was the same as the single-user environment to isolate only the variables of multiuser voice and multiuser avatar visualization of other participants to reduce effect bias (see Figure 4 for SUVR and Figure 5 for MUVR).

Figure 4. Single user experience with self-view (left -hand side), and classroom experience (right-hand side)

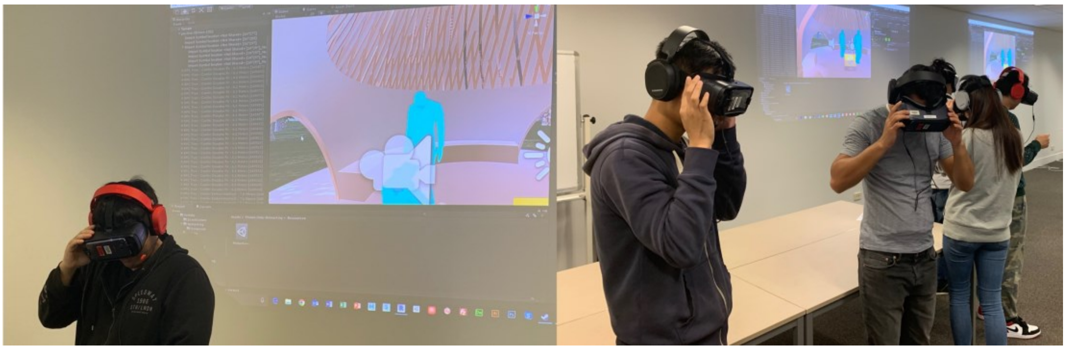

Figure 5. Multiuser experience with avatar kinematics (left-hand side), and classroom experience (right-hand side)

3.2. Study design

The study was performed as a within-subjects experiment using a mixed-methods research methodology per Creswell and Clark (2018) and the ethics granted for the study from the authors' institution. Data was collected from forty-eight (*n* = 48) voluntary recruited postgraduate construction participants from an Australian Higher Education institution in 2019. These participants were enrolled in a professional portfolio subject in the last semester of their Master of Construction degree. All data were recorded, stored, and de-identified under Australian Human Research Ethics.

Participants were randomly allocated into groups of 4-6 participants. After completing the single user condition, participants were moved to the multiuser condition. They were all provided with Samsung Galaxy S8 smartphones running Android Pie and Samsung Gear VR headsets with Steel Series 1 headsets. We selected these devices due to availability and to provide a consistent experience for the learners. Onboarding was presented for 5 minutes, delivered by the lead author. This included safety operation, assembly, task use, mobile IVR navigation, and communication method. The differences between the two experiences of the single user and multiuser were explained, including variance in the visual environment that being the use of simulated avatars and method of collaboration being the avatars and voice communication.

For both the single user (see Figure 4) and multiuser (see Figure 5) experiences, the participants were given 10 minutes per simulation to explore/communicate in the mobile IVR environment, 5 minutes per simulation to discuss their experience together as per Parong and Mayer (2018), and 20 minutes per simulation to complete an online Qualtrics survey (discussed in detail below). There was an additional 5-minute break between experiments to allow for transition and rest time.

3.3. Participant demographics

The participant demographics across the two experimental instances are presented in Table 1.

Table 1. Frequencies and percentages of participant demographics and technology competence

	Frequency	%		Frequency	%
Sex			Employment		
Male	20	42	Yes	2	4
Female	27	56	No	27	56
Undisclosed	1	2	No, but used to be	10	21
			Undisclosed	9	19
Age (mean = 26.7, median = 26.5)					
18-24	11	23	Technology Competence		
25-34	36	75	Extremely competent	6	13
35-44	1	2	Moderately competent	18	38
			Slightly competent	10	21
Country of residence			Neither competent nor incompetent	4	8
China	33	69	Slightly incompetent	1	2
India	5	10	Undisclosed	9	19
Australia	1	2			
Undisclosed	9	19	Primary mobile platform		
			Android (Google)	7	15
			iOS (Apple)	32	67
			Undisclosed	9	19

3.4. Data collection and instrument validation method

Self-reported measures in the form of an adapted questionnaire (see Table 2) were used to measure IVR usability and experience. The questions were adapted from the Nelson/Norman Group (see https://www.nngroup.com/articles/usability-testing-101/) leaders in software usability and Manis and Choi (2019) Virtual Reality Hardware Acceptance Model (VR-HAM), which is an extension to the original Technology Acceptance Model (TAM) proposed by Davis (1985).

Table 2. Immersive mobile virtual reality usability survey items

Construct	Item	Questionnaire item
IVR Utility	UTL1	The visualization is accessible or available for use at any time
	UTL2	The visualization is affordable in terms of monetary cost or efficiency in terms of time
	UTL3	The visualization is responsive, robust, and stable (error-free) in use (e.g., there are no problems with motion sickness, frame rates, or general software bugs)
IVR Engagement	ENG1	The novelty, aesthetics, or feedback afforded by the visualization focuses attention and involvement on the learning objective
	ENG2	The visualization is motivating, making the learner want to complete the learning objective
IVR Experience	EXP1	The visualization allows the accomplishment of the learning objective
	EXP2	The visualization allows for interactive variable manipulation, e.g., rotation, time, scene objects.
	EXP3	The visualization provides confidence in meeting the learning objective
	EXP4	The visualization provides effective or ease of re-establishing proficiency of the learning objective after a period (length) of time of the activity
	EXP5	The visualization allows for spatial translation (movement) of your (the users) viewpoint
	EXP6	The visualization provides a clear interface design to observe (view) and interpret the learning objective
	EXP7	The visualization provides an accurate representation of the real world (including visual, touch, and sound)
	EXP8	The visualization supports the discussion of learning objectives between stakeholders (instructor, learners, others)
	EXP9	The visualization allows emergent, creative, playful discovery towards the learning objective

All items were measured on a five-point Likert scale from strongly disagree to strongly agree. This addresses the concerns of subjective personality traits, as highlighted by Radianti et al. (2020) by quantifying the participants' perception of mobile IVR Usability. The survey instrument was administered as an online Qualtrics questionnaire per ethics via QR code using a unique identifier.

The analysis of the validity and reliability of the measurement model and the analysis of the path model were undertaken using the component-based PLS-SEM (Smart-PLS 3.3.0) software. The model includes three reflective constructs as three dimensions of mobile IVR usability, given that indicators are assumed to be caused by the latent variable. These are mobile IVR Utility with three items, mobile IVR Engagement with two items, and mobile IVR Experience with nine items.

We assessed the validity and reliability of the measurement model by conducting a confirmatory factor analysis (CFA) to assess reliability, convergent validity, and discriminant validity of the constructs. We assessed convergent validity with three metrics: average variance extracted (AVE) and composite reliability (CR), and Cronbach's Alpha. The instrument's convergent reliability was evaluated through Cronbach's alpha (Alpha) at 0.95. The results exceeded the minimum value proposed by Nunnally (1978) with a Cronbach's alpha > 0.7.

The inter-correlation between constructs was not above 0.9, which is in line with Pavlou, Liang, and Xue (2007). The AVE of mobile IVR Utility (0.619), mobile IVR Engagement (0.678), and mobile IVR Experience (0.663) were higher than 0.5 (Fornell & Larcker, 1981). The composite reliability (CR) values were between 0.762 and 0.952, higher than 0.7 (Fornell & Larcker, 1981). See Table 3 for more details. With the above said, we conclude that the criteria for convergent validity are met.

Table 3. Convergent validity and reliability of the mobile IVR usability model

Variable	Cronbach's Alpha	rho_A	Composite Reliability	Average Variance Extracted (AVE)
IVR Engagement	0.750	0.781	0.762	0.619
IVR Experience	0.949	0.952	0.950	0.678
IVR Utility	0.853	0.862	0.854	0.663
IVR Usability	0.951	0.955	0.952	0.589

Regarding the discriminant validity, the inter-correlation of constructs did not exceed the square root of the AVE of either of those compared constructs see Table 4. The square root of the AVE of the three dimensions of mobile IVR Usability is 0.787, 0.823, and 0.814; thus, we can conclude that the discriminant validity is met. The mobile IVR Usability analysis was performed via one-way repeated measures ANOVA and two instances of one-sample *t*-test. The analysis of the individual constructs was conducted via correlation and frequencies comparison.

Table 4. Discriminant validity of the mobile IVR usability model

	IVR Engagement	IVR Experience	IVR Utility	IVR Usability
IVR Engagement	0.787			
IVR Experience	0.889	0.823		
IVR Utility	0.527	0.765	0.814	
IVR Usability	0.925	1.034	0.861	0.767

As per Creswell and Clark (2018) the quantitative data was also reflected upon with follow up qualitative data. This was achieved using both a participant opinion sentiment of the visualization methods collected through the Qualtrics survey and follow up reflective essays. The participant sentiment was collected at the time of the experiment which is presented in the results below. The 300-500 words reflective essay was submitted anonymously by the participants fourteen days after the experiment and linked to their course learning outcomes which is used in combination with the quantitative data as per the mixed methods approach.

4. Results

Data were analyzed in the IBM SPSS statistics package version 26.0.0.1. A comparison of IVR Usability in both single (SUVR) and multiuser (MUVR) is presented in Figure 6. The Usability means and adjusted 95% confidence intervals, as noted by Loftus and Masson (1994) for the SUVR, and MUVR conditions are displayed.

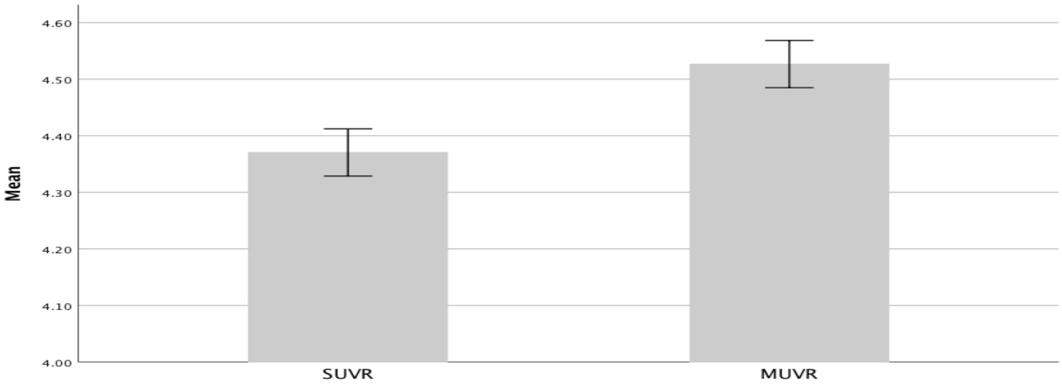

Figure 6. Mobile IVR Usability means and 95% confidence intervals for SUVR and MUVR

To test the hypothesis that for SUVR (M = 4.408, SD = 0.447) and MUVR (M = 4.564, SD = 0.434) mobile IVR Usability means were not equal, we used a one-way, repeated-measures ANOVA, followed by post-hoc one-sample t-tests to test the mobile IVR Usability difference to the baseline and the intervention measurements. Prior to conducting the analysis using parametric tests, we verified the normality of the distribution using a z-test for normality test using skewness and kurtosis (Kim, 2013). We obtained the z-score by dividing the skewness g = -0.522 (SE = 0.343) and kurtosis = -1.114 (SE = 0.674) values their standard errors resulting in values of and -1.278 and -.165, respectively. Both values were under the threshold of 1.96 (at α = 0.05). We consider that the assumption of normality of the sample is satisfied.

The assumption of homogeneity of variance was tested (Morgan, 1939; Pitman, 1939) based on a t-test method found in Gardner (2001) and satisfied at t = 0.747 (at $p < .05$). The assumption of normality for the t-test was considered satisfied as the skewness and kurtosis were at 0.513 and 2.715, respectively, which is less than the thresholds allowed for t-test (skewness <|2.0| and kurtosis <|9.0|) as per (Posten, 1984).

A repeated-measures ANOVA determined a significant effect of MUVR on the mobile IVR Usability of the visualization, $F(1, 47) = 14.18, p < .001, \eta^2 = .232$. These results suggested that the visualization was significantly more usable in terms of mobile IVR when used in a multiuser environment. Regarding the individual dependent variables, a repeated-measures ANOVA for mobile IVR Utility showed significant main effects for the MUVR intervention, $F(1, 47) = 11.34, p = .002, \eta^2 = .194$. This is also the case with the mobile IVR Experiences construct, which also showed significant main effects for the MUVR intervention, $F(1, 47) = 11.33, p = .002, \eta^2 = .194$. However, the mobile IVR Engagement construct did not show a significant main effect for the MUVR intervention.

A one-sample one-tailed t-test was run to determine whether the SUVR score in recruited participants was greater than neutral (neither agree nor disagree), defined as an SUVR score of 3 on the Likert scale. Mean SUVR score (4.393 ± 0.444) was higher than the normal SUVR score of 3.0, a statistically significant difference of 1.393 (95% CI, 1.267 to 1.519), $t(47) = 22.20, p < .001$. Thus, the SUVR mean was statistically significantly higher than the threshold of 3.

A one-sample one-tailed t-test was also run to determine whether the MUVR score in recruited subjects was greater than neutral (neither agree nor disagree), defined as a MUVR score of 3. Mean MUVR score (4.504 ± 0.518) was higher than the neutral MUVR score of 3, a statistically significant difference of 1.504 (95% CI, 1.357 to 1.651), $t(47) = 20.55, p < .001$. Therefore, the MUVR mean was statistically significantly higher than the measured mobile IVR usability threshold of 3. The SUVR and MUVR survey results are presented in Table 5, showing the comparison of the construct variable means and the correlations between the pairs. A paired-samples t-test of all the items was performed to compare items across all the constructs and presented in Table 6.

Table 5. Comparison of constructs means and correlations between SUVR and MUVR pairs

Pair	SUVR			MUVR			Correlations		
	Mean	*SD*	Err	Mean	*SD*	Err	MDif	Cor	Sig.
IVR Engagement	4.464	0.486	0.075	4.560	0.471	0.073	-0.095	0.355	.021
IVR Experience	4.362	0.418	0.064	4.553	0.441	0.068	-0.191	0.648	< .001
IVR Utility	4.111	0.578	0.089	4.310	0.692	0.107	-0.198	0.840	< .001
IVR Usability	4.323	0.412	0.064	4.502	0.429	0.066	-0.179	0.744	< .001

Table 6. Paired sample *t*-test of construct items highlighting differences between the two conditions per item

Pair	Mean	*SD*	Std. Error Mean	*t*	*df*	Sig. (2-tailed)
UTL1	0.063	0.727	0.105	0.596	47	.554
UTL2	-0.146	0.505	0.073	-2.001	47	.051
UTL3	-0.437	0.741	0.107	-4.09	47	0
EXP1	-0.167	0.663	0.096	-1.741	47	.088
EXP2	-0.083	0.577	0.083	-1	47	.322
EXP3	-0.062	0.633	0.091	-0.684	47	.497
EXP4	-0.208	0.617	0.089	-2.338	47	.024
EXP5	-0.104	0.722	0.104	-1	47	.322
EXP6	-0.167	0.519	0.075	-2.224	47	.031
EXP7	-0.458	0.922	0.133	-3.446	47	.001
EXP8	-0.125	0.57	0.082	-1.52	47	.135
EXP9	-0.125	0.444	0.064	-1.952	47	.057
ENG1	-0.104	0.592	0.085	-1.219	47	.229
ENG2	-0.062	0.633	0.091	-0.684	47	.497

Correlations were tested between the MUVR constructs against age and technology competence, and the significant correlations are presented in Table 7.

Table 7. Significant Correlations between MUVR mobile IVR Usability constructs against age and technology competence (Spearman's correlation coefficient is denoted by r_s)

Construct	r_s	Sig. (2-tailed)	*N*
What is your age group?			
IVR Engagement	0.390	0.014	39
IVR Experience	0.420	0.008	39
IVR Usability	0.400	0.012	39
How competent do you consider yourself when using technology?			
IVR Engagement	-0.324	0.044	39

The results of the collected qualitative SUVR and MUVR reflective opinion (sentiment) comments were collected at the time of the experiment. The constructs of mobile IVR Usability are presented as frequencies of participants that commented on the concept (or synonyms) in Table 8. The similarities between the visualization methods in the comments were evident, including a common sentiment of IVR Engagement, IVR Utility and IVR Usability across both methods. The primary difference was in IVR Experience for the MUVR approach. Qualitative data from the reflective essays is presented below in the findings and discussions to inform the quantitative data as per the mixed methods approach.

Table 8. Frequencies of the participant reflective opinions of SUVR and MUVR mapped to constructs

Pair	SUVR		MUVR		
	Count	%	Count	%	
IVR Engagement	11	23%	8	17%	engaging, interesting, fun, cool, exploring, want to
IVR Experience	8	17%	15	31%	experience, feel, communication, voice, people
IVR Utility	12	25%	9	19%	use, practical, useful, good to use, easy to control, helpful
IVR Usability	24	50%	22	46%	good, great, nice, fantastic, awesome, perfect, amazing, impressive, better
Negative	7	15%	8	17%	dizzy, price, slow, or any other negative comment

5. Findings and discussions

To answer the research question, we measured mobile IVR Usability of both the SUVR and MUVR visualizations, comparing results using parametric statistical tests addressing the subjectivity concerns of Radianti et al. (2020). It is noted that the comparison between SUVR and MUVR is a repeated measure (within-subjects) comparison as per the experimental design. In both visualizations, participants performed well and similarly regarding the mobile IVR Usability. The one-sample *t*-tests showed that both the SUVR and MUVR visualization methods are usable in terms of mobile IVR Usability. This is further supported by the participant sentiment data shown in Table 8.

The ANOVA of the repeated measures showed that the MUVR results are statistically significantly higher than the SUVR, although not explicitly shown in the qualitative sentiment data collected at the time of the experiment. Subsequently, the strong positive correlation usability between SUVR and MUVR suggests that if the multiuser mode is enabled in the IVR system, the mobile IVR Usability of the system is expected to increase. This is consistent with the research on education use of IVR and the impact of communication, multiple avatar representation, and learners' experiences (Bailenson, 2018; Jensen & Konradsen, 2018; Radianti et al., 2020; Reisoğlu et al., 2017).

We conducted a comparison between the constructs' items and the independent variables, and the significant correlations are shown in Table 7. The results for age were in positive correlation to several construct items. As noted in previous literature by Manis and Choi (2019), there is typically a negative relationship between increasing age and perceived ease of use and usefulness as it relates to VR hardware. We argue that one of the reasons might be the very narrow age range for the majority of the participants (8 years), with 98% of the sample being between 23 and 31years old, and 76% between 23 and 28. To further unpack *how* mobile MUVR compares to SUVR in terms of IVR Usability, we discuss the constructs below.

5.1. Mobile immersive virtual reality engagement

The mobile IVR Engagement construct did not perform significantly better in MUVR than SUVR, which we argue is the result of varying technology competency between the randomly assigned participants. The participants that self-report as more competent with technology tend to be less engaged within the MUVR environment, as the correlation results suggest. Therefore, this can result in a conflict between the participants' motivation to complete the learning task as those that self-report as more competent are grouped with those that self-report as less competent.

However, the qualitative essay data suggests that MUVR is more engaging and motivating. Specifically, students share their reflections of the excitement they had, "This is definitely another exciting day." the sensory appeal "…VR technologies can alter our senses of the reality. Interaction played a major part under this construct, as found in statements like "it is amazing to feel that we are interactive to the model and other group members." The observation during the activity also supports that students felt more engaged during the MUVR activity. Students found the visualization to be motivating and made them want to learn and explore more, which is supported by the statements like, "It's really fun, that makes me have more interests to learn." This aligns with research in authentic learning that authentic environments maintain high levels of engagement (Herrington et al., 2014; Parong & Mayer, 2018) and that immersive and interaction leads to engagement (Allcoat & von Mühlenen, 2018; Huang et al., 2019; Hudson et al., 2019).

5.2. Mobile immersive virtual reality experience

The mobile IVR Experience in MUVR was significantly better for the participants when compared to SUVR. This is supported by both the sentiment and qualitative reflection data from the survey and essays.

First, regarding the accomplishment of the learning objective, which was spatial understanding of BIM models, the observation during the hands-on activities and the essays submitted show that the students found using the VR visualizations helped them learn. This is reflected in student comments from the MUVR experience, such as "…makes me have more interest to learn" and "Very active learning method, a good way to demonstrate your idea." We also explored the satisfaction with the visualization. This is illustrated by statements such as "we experienced the fantastic [VR] used in the construction industry" and "I gained a great deal of information about the BIM course and had a good experience using VR." The satisfaction of the MUVR experience is captured in the student comments: "the overall effects and video chatting were parts of this fascinating experience." This reflects the broader literature that IVR improves learning and leads to greater satisfaction (Jensen & Konradsen, 2018; Reisoğlu et al., 2017).

When examining the deeper learning or proficiency of remembering and retaining the knowledge after the activity, students reflected on the experience. This demonstrates memory retention and remembering intricacies of the visualizations in detail, even though the reflections were written two weeks after the activity. Parong and Mayer (2018) suggest that using VR may result in losing the capacity to retain memory and reflect. In line with that, we argue that the relatively short continuous VR times and having the learner to reflect after each activity in the survey and comment may have led to better retention evident in the essays.

Interaction is a core IVR characteristic (Radianti et al., 2020; Slater & Sanchez-Vives, 2016). Interaction is not unique to the MUVR instance and is found in many of the students' statements, such as "It really immersed me into that virtual world and saw clearly how it rendered and how it looks in different time of the day." However, of note was that interaction with other students was even more important to the students in MUVR, supported with statements like "…it still impresses me that I can interact with peers and study together …" and "it is amazing to feel that we are interactive to the model and other group members." This is in line with Dalgarno and Lee (2010), who suggest that immersive virtual environments lead to an increase in co-presence or user's perception of being there.

The movement of the user's viewpoint in the visualization is also linked to the interaction. The freedom of movement in any virtual world is essential. It relates to the perception of control, immersion, and engagement (Jensen & Konradsen, 2018; Slater & Sanchez-Vives, 2016). Even though the visualization offered only three degrees of freedom, students found the ability to move via their animated avatars in the IVR environment very engaging and fun, by using statements such as "In the scene, we can walk around at will…". The multiuser additions through avatars and voice added to this experience, supported with comments like, "…we can feel each other in the model, and it's funny that all of us jumped on to the tree outside the [pavilion]." This reflects the consensus that avatars lead to improved immersion (Oh et al., 2018; Steed et al., 2016).

Concerning the visualization providing a clear interface design for observation and interpretation, overall the visualization performed satisfactorily, which is supported by comments such as "In terms of multiuser [the visualization] will give a clear understanding collectively" and "It really immersed me into that virtual world …" All essay comments related to this item were found only in MUVR suggesting that co-presence was a factor in the participants' observation and interpretation. We note that both visualization environments were virtually the same. However, as the MUVR visualization was enhanced through interactive avatars and communication between the participants, this likely resulted in an increased perceived fidelity, as the inclusion of the multiuser features brings it closer to the real world. Participants' comments support this in MUVR with statements like: "more real in details" and "Good shadow of leaf and tree." In SUVR, the statements are less optimistic towards the fidelity, for instance: "…can see the virtual world as real[.] However it's still not good enough…" and "Image quality should be improved." The lack of personalization of the avatars could be a negative contributing factor in line with Waltemate et al. (2018). In addition to this, participants commented: "…the body shape images are not beautiful." However, communication in multiuser may also have had a counter effect to the avatar beauty, by increasing the reality of the environment, supported by comments like: "Interestingly, we can "walk" in this VR environment by moving our feet in reality, and when the audio function turned on, I could hear someone talking in the [pavilion]."

In the reflective essays, students relate communication to almost all other concepts, using comments such as, "It was observed that while doing it individually it was less effective but when it was done in group it created a better understanding of collaborative use of this technology." Students found the peer to peer communication in a multiuser VR environment to be very important in construction, by stating: "[VR technologies] … they make people communicate better." and "Effective communication is the essential part for any construction project." It was strongly expected that this feature would be dominant in the MUVR, which is supported by the fact that almost none of the students talk about it in a single-user context. This suggests that the conversational aspects of multiuser IVR environments, as discussed by Bower et al. (2017) and the social presence (Oh et al., 2018) represented by avatars may have an effect on learner communication and their experience within the IVR environment.

Concerning the emergent, creative, and/or playful discovery allowed by the visualization, students, in general, found the VR environment to be fun and engaging: "It's very cool to stand on roof.", "It's really fun ..." and "Makes me feel like exploring more." Overall, the visualization supported students' creativity. Some students perceived MUVR more fun and some even as game-like, stating: "The feeling in multiplayer model is like playing the multi players games or online games thought the VR." Perceiving the MUVR experience in a gameful way can increase the engagement and further motivate the learners in meeting the learning objective (Dalgarno & Lee, 2010).

5.3. Mobile immersive virtual reality utility

In exploring the utilitarian dimension of mobile IVR, MUVR performed significantly better when compared to SUVR. Even though the same interface was used, the addition of the avatars, voice communication, and social interaction may have led to perceiving the system as more complex, and because there were no slowdowns or crashes, better to use. The issues with motion sickness that some of the participants experienced were not unique to either of the instances. Concerning the responsiveness, the arguably slow mobile devices were not observably different between the instances. The addition of the social element may have mitigated or lessened some of the adverse effects, evident in comments such as “when [used] for more than 5min I feel a little bit headache. But it is really f[u]n to see everyone [on] the same place”. This would be in line with the research of Oh et al. (2018) and the role of avatars and social interactions on presence.

6. Study limitations

There are limitations within the study, with only subjective self-reported measures used, a population sample of 48 learners within a single subject, three degrees of freedom head-mounted displays in the form of the Samsung Gear VR, now a discontinued technology, and a narrow age band. There are limitations with the instrument design, as many questions have been merged to reduce the impact on the participant’s time to complete the questionnaire and should be expanded in future research. Counterbalancing should be done in future studies to reduce the carryover effect, including using a 2X2 design using different environmental conditions, but this would require more participants. Therefore, this study can be considered a launchpad for future research exploring the causes of the evolution of the enhancement that multiuser mobile IVR provides, expanding beyond the scope of AEC education. Future research should focus on larger population sample sizes, counterbalancing of groups, new six degrees of freedom mobile HMDs, and improved visual capacity of new hardware devices across different disciplines.

7. Conclusions

With BIM adoption increasing in the AEC industry, this has led to integration difficulty in educational practice. IVR and mobile pedagogy has been shown to assist in education and authentic learning environments. In this study, participants observed a BIM visualization over a 24-hour transition simulating the day-night lighting change using mobile IVR technology. Participants experienced both single and multiuser visualizations with the difference between the experiences being the addition of visual avatars and voice communication capability. The students were able to visualize not only their self-avatar but that of their peers in the virtual environment. This setup also facilitated enhanced affordances such as agency, perception, and peer learning between the students allowing for collaborative navigation and synchronous communication discussion of the environment in the multiuser vs. an asynchronous approach in the single-user experiment. This study found that the perceived mobile IVR usability of MUVR to be higher than SUVR. Implementing the multiuser functions in the experiment engaged the learners on a different level and enhanced the overall learning experience. Although the study revealed that multiuser facilitates a better learning environment for learners, we do not assert that using multiuser mobile IVR is always the best way given increased costs associated with development and deployment. Therefore, we propose integrating mobile IVR and specifically multiuser within the course offerings when appropriate and achievable.

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