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Leveraging Immersive Virtual Technology for Job Hazard Analysis

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Abstract

Construction project teams often perform job hazard analysis (JHA) to identify risks and controls. Typically, an experienced worker leads a JHA session, because novice workers may not identify all hazards. Virtual reality (VR) applications, which have improved significantly in domains such as manufacturing and education, have the potential to increase JHA quality in a range of situations. The effectiveness of a VR application for JHA has not, however, been explored in depth, and this research aims to begin to fill that gap. Two interventions, a VR-based application for JHA and a paper-based JHA, were designed, developed, and implemented to measure their effectiveness. The VR-based JHA was more effective than the paper-based JHA, although statistical significance could not be established due to the small sample size. This report discusses the possible reasons for the successes and failures of these JHA approaches.

Key Findings

1. The research team successfully designed, developed, and tested an innovative tool (virtual reality application) to perform job hazard analysis.
2. Participants using the virtual reality-based JHA application performed better than those using the paper-based JHA approach, but the difference in the mean JHA scores of the groups was not statistically significant.
3. Participants' VR experience did not affect their JHA scores.
4. Participants with construction management or civil engineering background did not score higher than other participants.
5. VR-based JHA provided an immersive experience for all participants.

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Introduction

The U.S. construction workforce is aging, with a median age of 42.9 years in 2019 (US Bureau of Labor Statistics 2020). In 2020, more than 44% of the construction workforce was over 44 (US Bureau of Labor Statistics 2020). See Figures 1 and 2. To meet labor shortages, thousands of new workers are expected to enter the industry in the coming years. Integration and training of new workers will create a substantial increase in safety challenges for an industry that continues to have problematic safety outcomes, including about 1,000 annual deaths (U.S. Bureau of Labor Statistics 2022) and myriad consequences for individuals, families, organizations, and society. An innovative strategy to perform job hazard analysis (JHA) is important to protect workers from safety-related issues.

Traditionally, project teams perform JHA to identify risks and controls, and they are typically led by safety professionals and experienced workers (CCOHS n.d.; Roughton and Crutchfield 2011). There are likely to be situations in the future when less experienced and novice workers will represent a large percentage of a construction crew, and research indicates that when novice employees perform JHA, they frequently fail to identify all hazards (Albert and Hallowell 2012; Rousseau and Libuser 1997). Current low-tech tools designed to support JHA lack visualization elements, so experienced workers can typically identify hazards better than novices because they have performed similar tasks previously. In many cases, only generic JHAs are used, missing an opportunity to incorporate project-specific features. This situation leaves a significant opportunity to supplement existing tools, such as hazard identification methods, with state-of-the-art visual-based tools to create a new suite of preventive safety systems for the construction industry's future and its workforce.

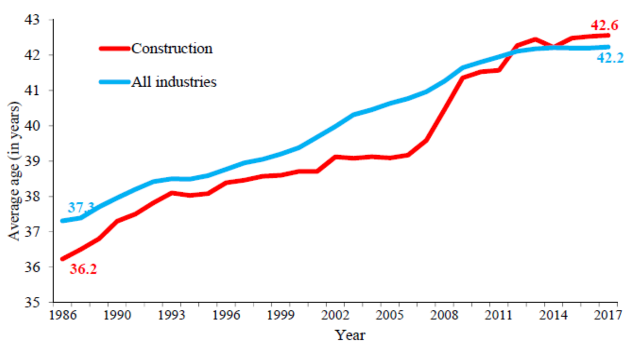

Figure 1. Average age of workers, construction versus all industries (Sokas et al. 2019)

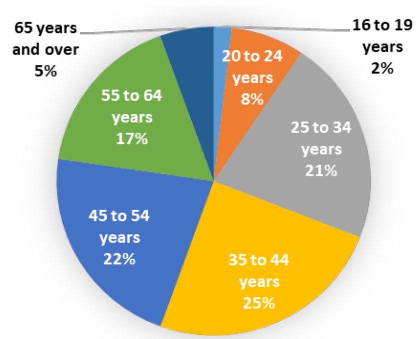

Figure 2. Percentage of all construction workers by age, 2020. (US Bureau of Labor Statistics 2020)

Ideally, supervisors and workers carry out JHAs with the help of safety and health personnel, a time-consuming process because the JHAs are complex (Department of Energy n.d.). In many cases, however, the JHA form is only read to workers during a pre-work meeting. Each participant is required to acknowledge the information by signing the form, which is designed to ensure that every worker knows the potential hazards and mitigation techniques related to their job (Zhang et al. 2015). This type of acknowledgment also may be used legally by some project participants.

Moreover, due to the unique nature of construction projects, each JHA is different. Current JHA relies heavily on individual safety managers or the superintendent's manual efforts to recognize potential safety hazards (Kim et al. 2016). Studies have shown that construction workers and supervisors cannot identify more than half of the hazards in their work area (Albert et al. 2017). Studies in Australia found that new workers were unable to recognize 57% of safety hazards (Bahn 2013). A hazard recognition method based on checklists is not effective because such lists are based on experience and injury records, which are not generalizable (Albert et al. 2014b).

Computer programs are often used to create building information models (BIM) of architectural and engineering designs. The building information model is the digital description of every aspect, such as building geometry, spatial relationships, characteristics of building components, and geographical information of the built asset (Kubba 2016)The use of BIM for construction is increasing, but there is still an apparent disconnect between hazard identification and information models (Zhang et al. 2015). Digital models are available primarily to management personnel, such as project managers, superintendents, and supervisors. Front-line construction workers rarely use these digital models to improve performance on construction sites (Mirarchi et al. 2018).

Visualization tools can assist designers and construction managers in incorporating safety into the design and construction. The use of VR has been found to help create safer designs (NSC 2014). Several studies indicate the benefits of visualization-based technologies such as BIM (Kiviniemi and Markku Kiviniemi Kalle Kähkönen, Tarja Mäkelä & Maija-Leena Merivirta 2011), game technologies (Din and Gibson 2019; Guo et al. 2012), virtual reality (VR) tools (Zhang et al. 2020), and augmented reality applications (Pereira et al. 2019) for hazard identification. The use of BIM models with their construction simulation potential has been suggested to improve safety through design (Rodrigues et al. 2017, 2020). Safety through design is a safety management approach that can be highly effective. However, when hazards need to be identified by workers and field personnel before or during construction, visual-based tools are rarely used.

Currently, VR is mostly used for safety training of workers. The purpose of VR training programs is to provide a safe working environment where users can practice and improve their ability to recognize and control construction hazards (Zhao and Lucas 2015). Some researchers recommended the use of BIM with VR in addition to JHA training. As BIM becomes more widely used in construction, there is also interest in using digital models to perform JHA (Rajendran and Clarke 2011). However, there is no study on the use of BIM in immersive virtual reality (IVR) for JHA. IVR is a technology that uses powerful hardware and software to create a realistic, digitally simulated environment, with the virtual environment mostly presented on a head mounted device rather than a computer screen. On the other hand, several studies reported the benefits of BIM and VR for training purposes (Alizadehsalehi et al. 2020; Le et al. 2014).

BIM and VR can be used for construction safety during pre-task planning. By interacting with the digital elements to be built, workers can identify hazards and control measures more effectively. The use of VR can be used to evaluate the sequencing of high-hazardous construction tasks, such as the erection of steel, the installation of hoists, and the erection of tower cranes. Conflicts with other activities in that area can be eliminated through evaluation. This results in the task being completed faster and safer.

This research project aims to harness the potential of a digital model visualized in a virtual environment to improve JHA quality, eliminate risks such as falling and being struck by objects, and explore just-in-time training opportunities. The outcome of this study is a collaborative functional process in which a model is accessible on a head-mounted display during JHA performance.

Objectives

The following are the objectives of the study.

Objective 1. Design workflow for efficient deployment of construction-ready digital models in immersive virtual environments.

Objective 2. Implement a collaborative and interactive platform for hazard identification in immersive virtual environments.

Objective 3. Identify hazards, including falls and struck by objects, using the platform deployed in aim 2.

Methodology

The experimental design involved two groups: a paper-based JHA group and a VR-based JHA group. The approach compared the traditional, paper-based approach and the new, VR-driven approach, using different participants with the two approaches. The proposed system used IVR to visualize an existing BIM to conduct collaborative and interactive job hazard analysis sessions. The IVR allowed immersion in an artificial environment where users could think as they do in actual construction work. Figure 3 presents the overarching idea of tool design, development, and evaluation.

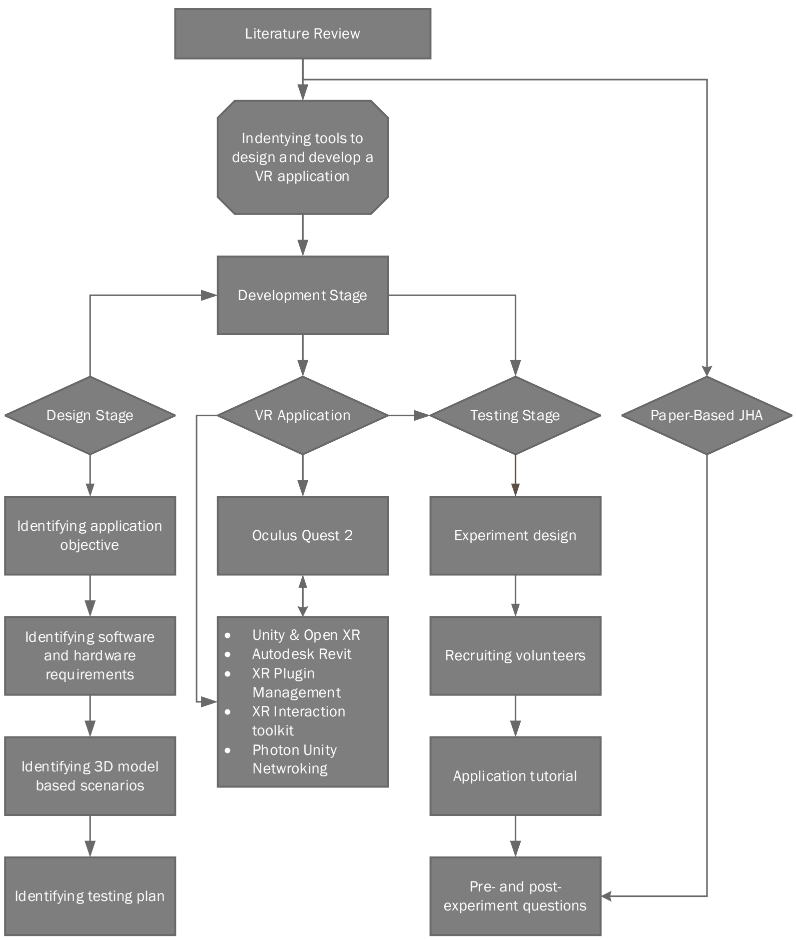

Figure 3. Research workflow

After the researchers completed design and development, four industry experts evaluated the VR application and provided feedback to improve it. Experts were construction professionals with extensive knowledge of construction processes and JHA's. Experts were invited from the industry advisory board of the construction management department and from the authors' personal contacts. Table 1 shows the background of the experts.

Table 1. Expert profile

Expert	Construction Industry Experience	Role
Expert A	18 years	Academician and industry professional
Expert B	10 years	Superintendent
Expert C	7 years	Designer (Architect)
Expert D	21 years	Senior Vice President

The experts provided feedback on the overall implementation process, including research design and application performance. After addressing the comments of the experts, paper-based and VR-based interventions were administered to students recruited from the University of Houston for a full-scale evaluation. Table 2 presents the academic background information of the participants.

Table 2. Participants and academic background

Group		N
Paper-Based JHA	Construction Management	4
	Civil Engineering	1
	Computer Science	2
	Industrial Engineering	2
	Petroleum Engineering	1
	Total	**10**
Application-Based JHA	Construction Management	4
	Civil Engineering	1
	Computer Science	1
	Industrial Engineering	3
	Hospitality Management	2
	Total	**11**
Total	Construction Management	8
	Civil Engineering	2
	Computer Science	3
	Industrial Engineering	5
	Hospitality Management	2
	Petroleum Engineering	1
	Total	21

Visual Job Hazard Analysis Application

The JHA system uses IVR to visualize a building information model, through which the researchers conducted collaborative and interactive job hazard analysis sessions. The IVR allows immersion in an artificial environment where users feel as they would in actual construction work.

The research team repurposed architectural 3D digital models from an existing construction project. In the entire model, the task selected for experiments to perform JHA was an external masonry wall modeled to satisfy the definition of level of development (LOD) 400 using Autodesk Revit. The information contained in a model created at the LOD 400 level is sufficient and accurate to construct the physical component. Models such as these can be used to measure models' quantity, size, shape, location, and orientation without referencing non-model data (Leite 2019). Table 3 describes typical hazards associated with bricklaying and their solution.

Table 3. Bricklaying hazard and solutions (CPWR 2022)

Hazards	Solution
Cold-related injuries and illnesses	Space heater, protective clothing
Eye injury	Eye protection
Fall from heights	Fall protection
Heat and sun exposure	Personal fall protection systems
Lifting and carrying (manual materials handling)	Adjustable tower scaffold, ergonomic design
Overhead work	Mast climbing work platform, ergonomic design
Skin contact with Portland cement	Gloves, hand washing station
Stooped postures	Mortar stand, mast climbing work platform, ergonomics
Stressful hand & wrist activity	Robot use, ergonomic hand tool

Confounding Variables

The dependent variable of this study is the JHA score. Confounding variables likely to influence it included participants' age, academic background, and VR experience.

Design of the Study

The participants completed JHA forms using both types of JHA tools, i.e., paper-based and virtual reality-based. The authors evaluated the quality of each JHA according to the rubric given in Table 3, and the comparison of the effectiveness of both types of tools was based on the JHA score. The following statistical analysis was performed.

An analysis of variance (ANOVA) was conducted using the JHA score as the dependent variable and other variables, such as interventions, as the independent variables. Using ANOVA, we can determine whether there are statistically significant differences between the interventions' JHA score means. This study has only one dependent variable, making it a univariate study.

The main effects of interventions were measured by the mean difference in JHA scores between interventions.

Procedure

To measure the effectiveness of the VR-based JHA application, a questionnaire methodology was used to document the responses of participants following each type of session. Pre-tests and post-tests were used in the intervention evaluations. Due to the relative newness of VR-based job risk analysis, no relevant surveys were found in the literature that could be incorporated into this study. Studies on serious games in construction engineering and management disciplines (Din and Gibson 2018; Din 2017) were consulted for further learning. As a result, the authors prepared survey instruments (pre- and post-tests) for review and approval by the Institutional Review Board at the University of Houston. The data collected was analyzed using descriptive and inferential statistical techniques. Quantitative analyses of the data are described in the following section. An ANOVA was used to determine the effect of the two independent variables, paper-based JHA and VR-based JHA. A factor analysis was performed to determine the effect of confounding variables.

Limitations of the Study

The sample size of this study was relatively small, with 21 participants; therefore, the results cannot be generalized. The participants of this study include construction management, civil engineering, computer science, electrical engineering, industrial engineering, and hospitality management students. Most of them have no prior construction knowledge, except for the civil engineering and construction management students. Due to this, they might have had difficulty understanding construction and engineering drawings, and so only scenarios related to low skill construction processes, such as bricklaying, were used in the tests. The application needs to be tested with students who study construction management to assess its performance on more complex construction tasks. The purpose of this study was to test the proof of concept. Thus, the researchers developed content, coded, and designed the VR application themselves. The quality of the application is not comparable to commercially available software. Several improvements were suggested, including better doodling control, better data entry form, and 3D navigation, which are necessary for a VR tool to be more effective. Thus, the authors plan to collaborate with a VR application designer to create a high-quality hazard identification tool.

Accomplishments And Results

Visual Job Hazard Analysis Application Development

Although VR is gaining the attention of architects, engineers, and construction professionals for design review and safety training, its use in construction work hazard analysis is minimal. One explanation for the low adoption rate in construction is that the development and implementation of VR applications are not as straightforward as other plug-and-play consumer applications and tools. VR requires the development of VR applications, which requires computer science knowledge. For non-programmers interested in developing VR apps for research and in-class use, resources such as development tools, guidelines, and system architecture knowledge are scarce.

The authors, therefore, dedicated significant resources to designing and developing a VR based JHA application. Arguably, it was the single largest deliverable in this project. The authors reviewed and documented the design and development processes of their VR-based collaborative visual JHA tool, basing their work on a literature review and consultation with construction professionals. The application was developed using the Unity game engine. The VR application was deployed on the Oculus Quest 2, a head-mounted device. Autodesk Revit was used to create the three-dimensional digital model that was used in the VR-based JHA. A cloud platform called Photon Server was deployed to implement collaborative learning. The authors evaluated the usefulness of the VR application. This application can be used in classroom teaching and collaborative hazard identification.

Based on the application development process, a conference paper was presented at the American Society for Engineering Education conference describing the design and development of a collaborative environment based on VR that can be used for construction education and visual JHA. The article contributes to the body of knowledge by documenting the application development process, including many software and hardware tools and best practices for designing and developing the application. The article also offers information on the guidelines and common pitfalls in the VR development process. Based on the test of the application, the authors plan to develop the application further. Figures 4 and 5 show screenshots of the application in which the user is inspecting, identifying, and annotating the BIM model.

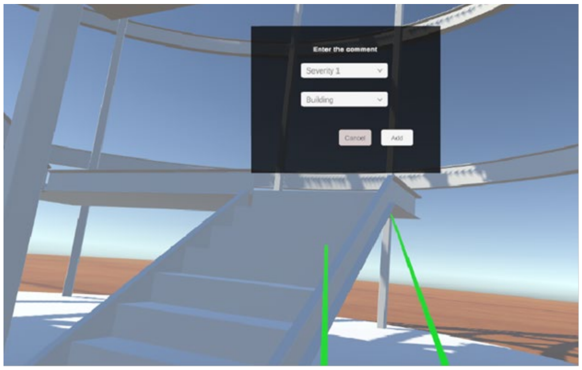

Figure 4. User performing comment annotation in the VR-based JHA application

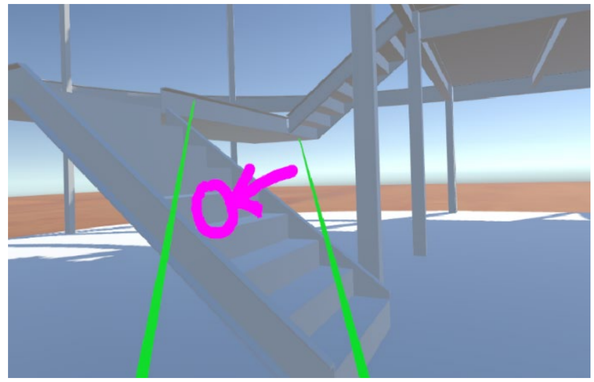

Figure 5. User performing doodle annotation in the VR-based JHA application

VR-based JHA Performance

Descriptive data analysis indicates that the mean of paper-based JHA was lower (M=7.4, SD=4.881) compared to the mean of VR-based JHA (M=11.27, SD=5.587), as shown in Table 4. Figure 6 illustrates the ranges of mean JHA scores of participants in the two interventions. Based on the box plot, paper-based JHA participants performed very differently from VR-based JHA participants.

Table 4. Descriptive analysis

	N	Range	Minimum	Maximum	Mean	Std. Deviation
Paper-Based JHA	10	15	3	18	7.40	4.881
Application-Based JHA	11	16	4	20	11.27	5.587

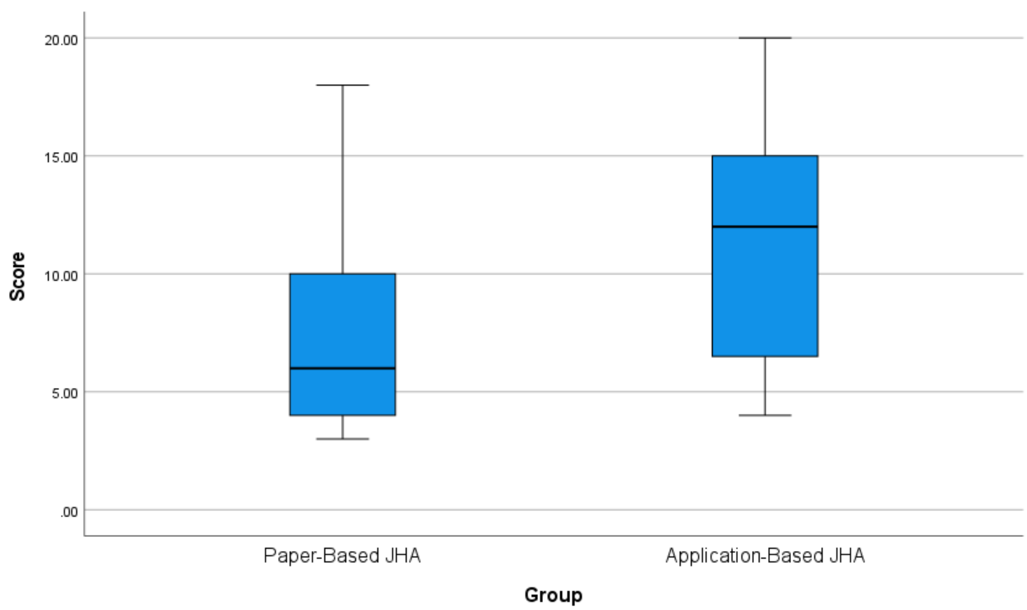

Figure 6. JHA score range

Statistical Comparison of VR-based JHA and Paper-Based JHA

To determine if the means of the two populations are equal, an independent sample t-test was conducted. As shown in Tables 5 and 6, for both interventions, the independent sample showed no significant effects on JHA score at the 0.05 level, $F (1, 19) = 2.835$, $t(19)=1.68$, $p=0.109$. There are no statistically significant differences between the mean scores of the paper-based and VR application-based JHA groups. There are two possible explanations for this outcome. First, the sample size is small (total N=21), and the task assigned to the analysis of hazards at work was too simple; even participants without construction knowledge were able to identify hazards.

Table 5. Analysis of variance

	Sum of Squares	df	Mean square	F	Sig.
Between Groups	78.561	1	78.561	2.835	.109
Within Groups	526.582	19	27.715		
Total	605.143	20			

Table 6. Independent samples test

		Levene's Test for Equality of Variance		t-test for Equality of Means							
		F	Sig.	t	df	Significance		Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
						One-Sided p	Two-Sided p			Lower	Upper
Score	Equal variances assumed	.237	.632	-1.684	19	.054	.109	-3.87273	2.30022	-8.68714	.94169
	Equal variances not assumed			-1.695	18.9	.053	.106	-3.87273	2.28478	-8.65523	.90977

Factorial Analysis

The impact of confounding variables (age, VR experience, and academic background) on the JHA score of any intervention was determined using an individual factorial design analysis. The results of the study were used to examine the main effects and interaction effects of these confounding variables on the JHA score.

VR Experience

A two-way ANOVA was performed to measure the influence of previous VR experience on the JHA score. Table 7 contains the results, which show that there no effect on JHA score.

Five participants who had used VR before earned average JHA scores of 10.00 (SD=5.413) in the VR-based JHA intervention; six participants who had not used VR before in the same intervention group had an average JHA score of 12.33 (SD=5.988). In all two interventions, the seven participants who had used VR before earned an average JHA score of 8.85 (SD=4.98), and 14 participants who never used VR scored 9.71 (SD=5.90). Therefore, the effect of the interaction between the previous VR experience and the intervention on the JHA score was not significant.

Table 7. Descriptive statistics, JHA score, VR experience of participants

Group	VR experience	Mean	N	Std. Deviation
Paper-Based JHA	Yes	6.0000	2	2.82843
	No	7.7500	8	5.36523
	Total	7.4000	10	4.88080
Application-Based JHA	Yes	10.0000	5	5.43139
	No	12.3333	6	5.98888
	Total	11.2727	11	5.58732
Total	Yes	8.8571	7	4.98092
	No	9.7143	14	5.90213
	Total	9.4286	21	5.50065

Academic background

Table 8 shows that four participants with a construction management background earned average JHA scores of 8.75 (SD=2.98) in the VR-based intervention and an average JHA score of 8.25 (SD= 6.84) in the paper intervention. Also, in the VR application-based JHA, three participants pursuing industrial engineering degrees received an average JHA score of 14.33 (SD=8.14), while in the paper-based intervention, two participants with an industrial engineering background received a JHA average score of 5.65 (SD=5.66). This shows that when construction task information was presented visually for this sample, users of non-construction backgrounds could also perform well in JHA.

Table 8. Descriptive statistics of academic background

Dependent Variable: JHA score

Group	Academic Background	Mean	Std. Deviation	N
Paper-Based JHA	Construction Management	8.2500	6.84957	4
	Civil Engineering	3.0000	.	1
	Computer Science	6.0000	2.82843	2
	Industrial Engineering	8.0000	5.65685	2
	Petroleum Engineering	10.0000	.	1
	Total	7.4000	4.88080	10
VR Application-Based JHA	Construction Management	8.7500	2.98608	4
	Civil Engineering	4.0000	.	1
	Computer Science	12.0000	.	1
	Industrial Engineering	14.3333	8.14453	3
	Hospitality Management	15.0000	4.24264	2
	Total	11.2727	5.58732	11
Total	Construction Management	8.5000	4.89898	8
	Civil Engineering	3.5000	.70711	2
	Computer Science	8.0000	4.00000	3
	Industrial Engineering	11.8000	7.29383	5
	Hospitality Management	15.0000	4.24264	2
	Petroleum Engineering	10.0000	.	1
	Total	9.4286	5.50065	21

Participant age

Using a two-way ANOVA known as factorial analysis, the authors determined how interventions affect the JHA score and the combined effect of age and intervention on the JHA score. In total, 13 participants (of those who participated in all intervention sessions) were 18-24 years old, seven were 25-34 years old, and one was 35-44 years old. Table 9 provides the mean JHA scores and standard deviations for all participants in both interventions. The average gain score of seven participants ages 18-24 years in the VR-based intervention group was 10.5 (SD=6.47); the average gain score of three participants between 25-34 years in the same intervention group was 14.00 (SD=3.46). According to these results, the performance of participants aged 25-34 was very high. In both intervention groups, seven participants ages 25-34 earned an average gain score of 12.28 (SD=4.8), the highest of any group. In the study, age did not significantly influence the JHA score. Table 10 presents the effect of age and interventions on the JHA score. According to the result, there was no statistically significant interaction effect between age and JHA interventions on the JHA score, $F(1,16) = 0.294$, $p = 0.595$. There was no statistical significance of the main effect of age, $F(2, 16) = 2.165$, $p = 0.147$.

Table 9. Descriptive statistics JHA score for participants' age

Dependent Variable: JHA score

Group	Age	Mean	Std. Deviation	N
Paper-Based JHA	18-24 years	5.0000	2.36643	6
	25-34 years	11.0000	5.77350	4
	Total	7.4000	4.88080	10
Application-Based JHA	18-24 years	10.5714	6.47707	7
	25-34 years	14.0000	3.46410	3
	35-44 years	8.0000	.	1
	Total	11.2727	5.58732	11
Total	18-24 years	8.0000	5.62731	13
	25-34 years	12.2857	4.82059	7
	35-44 years	8.0000	.	1
	Total	9.4286	5.50065	21

Table 10. Tests of between-subjects effects: age and intervention effect on JHA score

Dependent Variable: JHA score

Source	**Type III Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**
Corrected Model	201.429[a]	4	50.357	1.996	.144
Intercept	871.753	1	871.753	34.549	<.001
Group	82.286	1	82.286	3.261	.090
Age	109.268	2	54.634	2.165	.147
Group * age	7.406	1	7.406	.294	.595
Error	403.714	16	25.232		
Total	2472.000	21			
Corrected Total	605.143	20			

a. R Squared =.333 (Adjusted R Squared =.166)

Users' Feedback

We asked the users to respond to statements and questions about the VR-based JHA experience. Figure 7. presents the feedback of the participants. All participants liked the responsiveness of the VR environment. Moreover, half of the participants reported natural interaction with the model in the VR application. All users indicated that their experience was immersive. About 60% of the respondents rated their ability to adjust to the virtual environment experience as "very good," and the other 40% considered theirs "good."

About 72% considered their proficiency in interacting with the virtual environment to be “very good,” while only 9% rated themselves fair or neutral.

Interestingly, the menu available in the application was helpful to 82% of users. In comparison, one user (9%) considered the application menu “poor.” Overall, 73% of users considered their experience “very good,” three users considered their overall experience as “good,” and no one rated it as “poor.” For example, one user commented, *“It was a great experience, and I would definitely want to see this in the future.”*

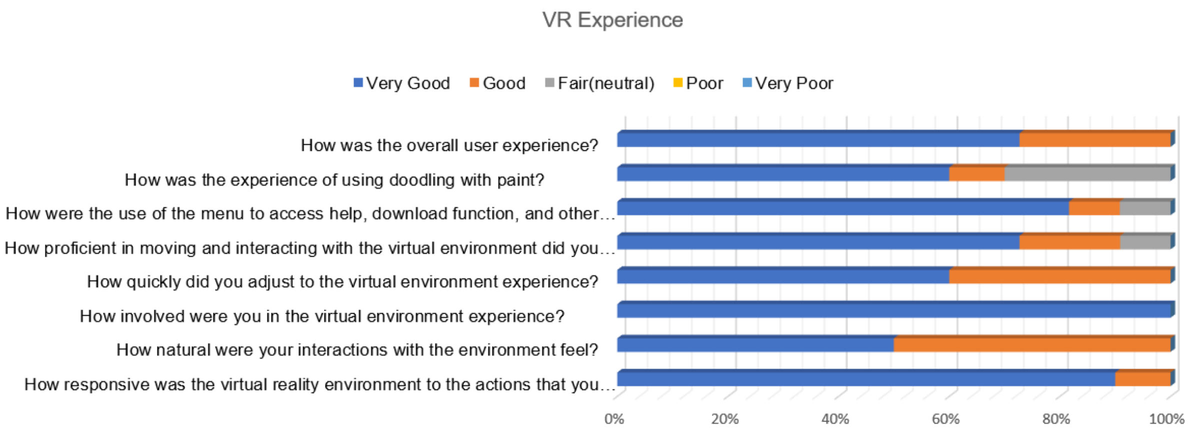

Figure 7. User evaluation of the VR-based JHA

Dissemination Plan

Journal articles and a conference paper will be written that describe the research study and findings and submitted for publication and presentation. Two related papers that do not directly address the study objective but were developed based on the understanding received from this project, have already been presented and published at two conferences.

Publications

1. Murari, H. S., Din, Z., and Spitzmueller, C. (2022). “Lessons learned from the development of an immersive virtual reality-based collaborative architecture, engineering, and construction (AEC) education environment.” *2022 ASEE Annual Conference, Construction Engineering Division*, American Society for Engineering Education, Minneapolis.
2. Murari, H. S., Din, Z. and Spitzmueller, C. (2022). “Investigating the feasibility of using virtual reality devices to present construction information in both mixed-reality and virtual-reality environments.” *Annual Conference CSCE 2022,* Canadian Society for Civil Engineering, Whistler, Canada.

Planned Publications

The research team is writing the following articles to disseminate the study results.

3. Sherman, R. and Din, Z. (2022). “A systematic review and analysis of the adoption of virtual reality in AEC education and practice.” *Journal of Construction Engineering and Management*.
4. Patel, M.A. and Din, Z. (2022). “Potential for job hazard analysis in a collaborative virtual reality environment.” *Safety+Health Magazine*.
5. Din, Z. and Murari, HS (2022). “An exploratory study of leveraging immersive virtual technology for job hazard analysis in construction.” *Safety Science*.

Changes/Problems

The project team faced two challenges during its implementation. First, a student researcher was hired a month late because the project began during summer break. Second, it was difficult to recruit participants. Since most architecture, engineering and construction (AEC) students were taking online classes and did not attend campus regularly, recruiting them for the application test was difficult. The authors recruited students from other programs to achieve the project's goals.

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