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Transforming Construction Safety Training into a VR-Based Serious Game in CEM Curriculum

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Transforming Construction Safety Training into A Virtual Reality-Based Serious Game in CEM Curriculum

Introduction

The awareness of safety and health hazards in the work environment is of utmost importance to the construction industry. Construction sites are inherently hazardous with various potential risks, including falls, electrocution, machinery accidents, and exposure to harmful substances [1]. Accidents and injuries at construction sites can result in project delays, increased costs, and litigation. A lack of awareness or negligence regarding safety measures can lead to severe injuries and even the loss of life. Therefore, emphasizing safety and health awareness is essential to protect workers' well-being and prevent accidents.

A safe working environment fosters a positive atmosphere and boosts employee morale [2]. Workers who feel secure are likely to be more productive and committed to their tasks [3]. Awareness of safety and health hazards enables project managers and workers to implement preventive measures and minimize the chances of disruptions. This contributes to cost-effectiveness and the timely completion of projects. Governments and regulatory bodies, including the Occupational Safety and Health Administration (OSHA), have established stringent safety standards and regulations for the construction industry. Compliance with these standards is not only a legal requirement but also essential for construction companies to maintain their reputation. Therefore, providing systematic training and education is essential to directly equip workers and managers with the knowledge needed to recognize and mitigate construction safety and health hazards.

Zhang et al. [4] state that Virtual Reality (VR)-based serious game learning has been proven effective in enhancing various safety and health training methods. The advancement of VR technologies presents an opportunity to revolutionize the delivery of safety and health training and education. The advantages of VR-based serious game learning stem from the specific circumstances and characteristics of the construction industry, as well as from construction engineering and management (CEM) education's need for experiential, scenario-based learning that is difficult to deliver in traditional classrooms. CEM educators have long relied on field trips, case studies, and personal experiences to familiarize students with the field scenarios and construction practices. However, site access can be limited, and there are legitimate safety concerns when inexperienced students set foot on a construction site and are exposed to its hazards. In contrast, serious games give students the opportunity to experience realistic site conditions in a simulated, virtual environment, without having to worry about the limitations mentioned.

VR-based serious games simulate scenarios that alert learners to the importance of accident prevention and safe site practices. They enhance learners' ability to identify potential on-site hazards and quickly devise solutions to control or mitigate them. By applying the knowledge of construction safety and health they have learned in real-world situations, students achieve the ultimate learning objective of construction safety and health education and training. From a pedagogical standpoint, serious games meet the growing need to implement problem-based, active, and hands-on learning strategies, as validated by several studies as effective teaching and learning approaches [5].

Recent advancements in VR technology provide significant opportunities to enhance safety training in the construction industry. Despite these developments and various studies on the application of VR in safety training, its integration into CEM curricula remains limited [4]. Furthermore, previous studies did not integrate pedagogical theory or offer gamified solutions for the CEM education and training [6]. To address these gaps, this study used a VR-based construction safety serious game developed by the first and second authors' previous research [7], which was based on Bloom's Taxonomy [8], and evaluated its acceptance among CEM students and industry professionals using the Technology Acceptance Model (TAM) [9].

Background

According to the Bloom's Taxonomy [8], a higher level of learning can be achieved when learners apply knowledge in a specific situation, analyze their understanding by identifying relationships within the overall context, and evaluate information to make informed judgments. These learning processes will enable learners to synthesize knowledge into a coherent whole that supports effective construction planning. Thus, learning by understanding and remembering alone does not allow CEM learners to achieve a high level of learning.

Serious games can offer open-ended challenges that learners can experience, similar to real-world situations. VR-based serious games can effectively reproduce conditions with actual hazards and demonstrate their harmful effects. Because of this ability to recreate complex environments and dynamic site conditions, various topics of CEM education that heavily rely on experiential learning, such as scheduling, sustainability, and construction safety and health training, have the greatest potential to benefit from serious games [7, 10, 11].

Learners can explore multiple solutions and compare their relative effects and outcomes within serious games. Thus, students can learn by doing and reflecting. They gain exposure to the underlying causes of safety and health issues on a virtual construction site, practice developing a hazard prevention plan, and evaluate processes that lead to an eventual outcome. Even when an accident occurs as a result of an incorrect safety decision, students can analyze their mistakes and understand related consequences, strengthening their ability to plan more safely. Authentic contents and real-world contexts promote learners' engagement, which plays a crucial role in enhancing students' motivation for learning [7].

The technical and functional aspects of serious games include continuous interactions and instant feedback. The sense of fun and enjoyment derived from a game's characteristics also positively affects learners' educational effectiveness. Furthermore, serious games provide students with greater opportunities to achieve higher levels of learning in Bloom's Taxonomy by allowing them to apply and evaluate their CEM knowledge and skills through unlimited trials, without worrying about the consequences of the outcomes.

Methods

A VR-based serious game was previously developed for CEM learners to identify safety and health issues and solve quiz questions related to OSHA regulations by navigating a virtual job site. The theoretical framework for developing the serious game is further elaborated by Lee et al. [7]. In the current study, a specific VR training module based on concrete construction activities in a university campus building project was selected for the experiment to evaluate the acceptance of the training module among CEM students and industry professionals. The module focuses on slab and beam construction and includes nine questions designed to assess participants' knowledge of OSHA regulations related to construction safety and health hazards. This module simulates various fall-related hazards, including hole covers, floor and window openings, shoring systems, scissor lifts, concrete pumping systems, mobile scaffolds, and ladder setups. In this experiment, Meta Quest 3 was used as the experimental VR device. A Dell Alienware m16 R2 gaming laptop was connected to it to test the VR training module. Figure 1 shows the instruction page for the VR training module developed for the experiment.

Construction management program students from Central Connecticut State University and construction industry professionals in the Connecticut state area were recruited as research participants in this study. The participants navigated the 3D virtual construction site from a first-person perspective and addressed construction safety–related problems by interacting with 3D question marks. By observing animations, identifying potential risk factors that could lead to fatality or injury, and completing construction safety-related problem sets, participants evaluated hazards and learned the corresponding safety regulations (Figure 2). The concrete construction module contains five activities, each tied to specific safety hazards and applicable regulations. Throughout the game, participants encountered quiz sets and received feedback on their performance, including scores, costs, and accident probabilities based on their responses.

For example, one of the five activities is about a hole cover that is not properly secured, such as by nailing the cover edges, or clearly marked to indicate a floor hole. Once passing through the question mark, participants are prompted with questions about the identified hazard in the scene (Figure 3).

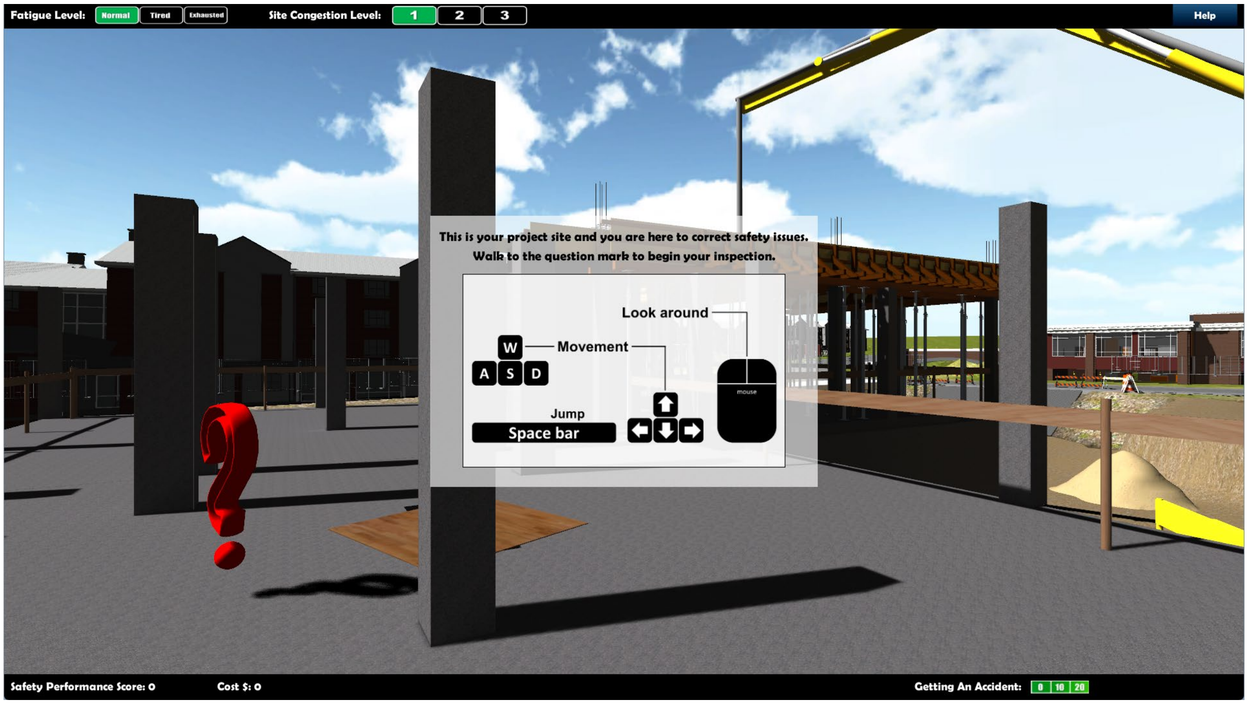

Figure 1. Instruction Scene of the VR Safety Training Module for Concrete Construction Activities

Figure 2. Hazards Recognition Activities in the VR Safety Training

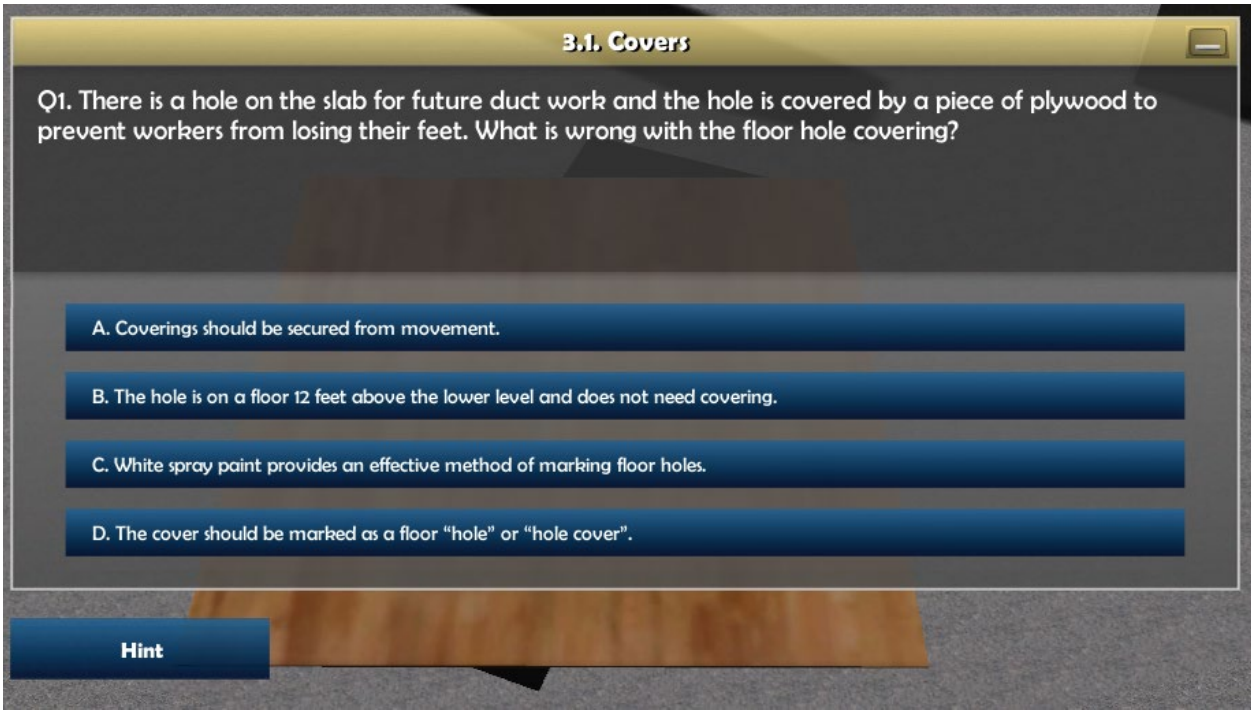

Figure 3. Example Question Regarding Fall Hazards due to Incorrectly Covered Hole on the Slab

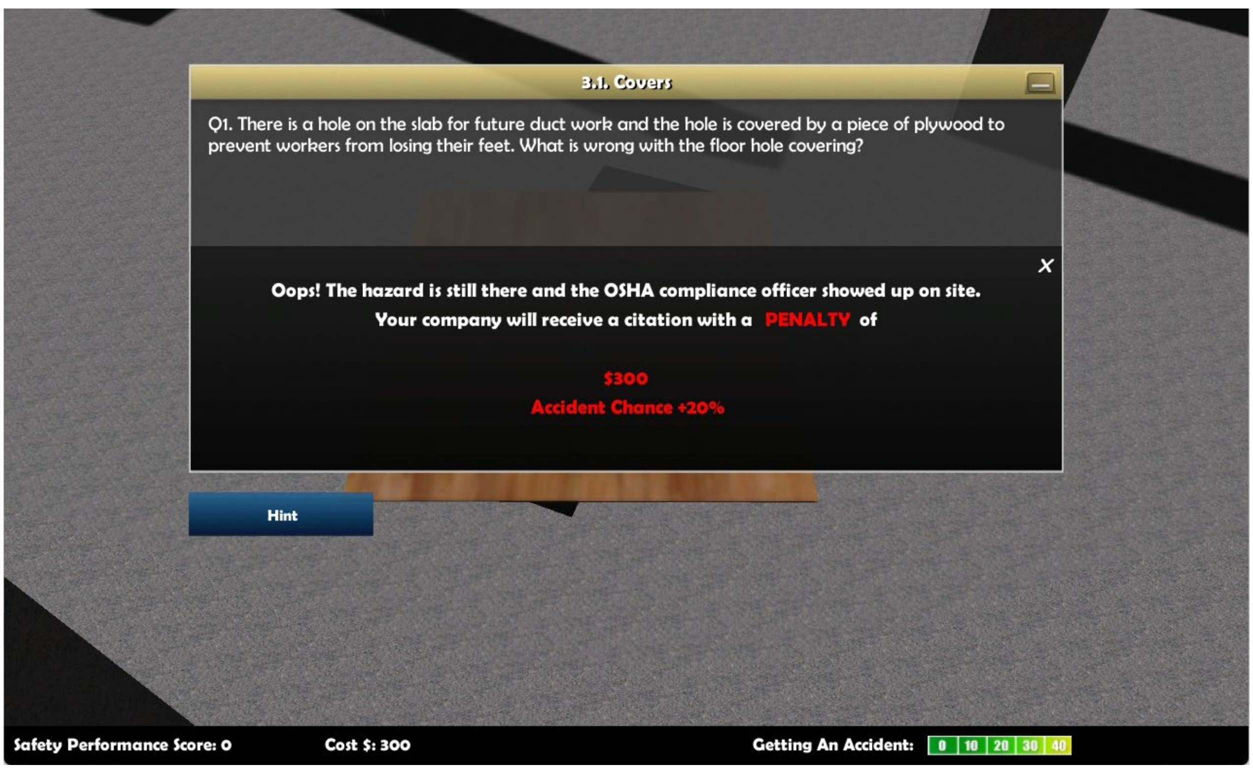

Figure 4. Learners' Feedback on Their Responses to Questions

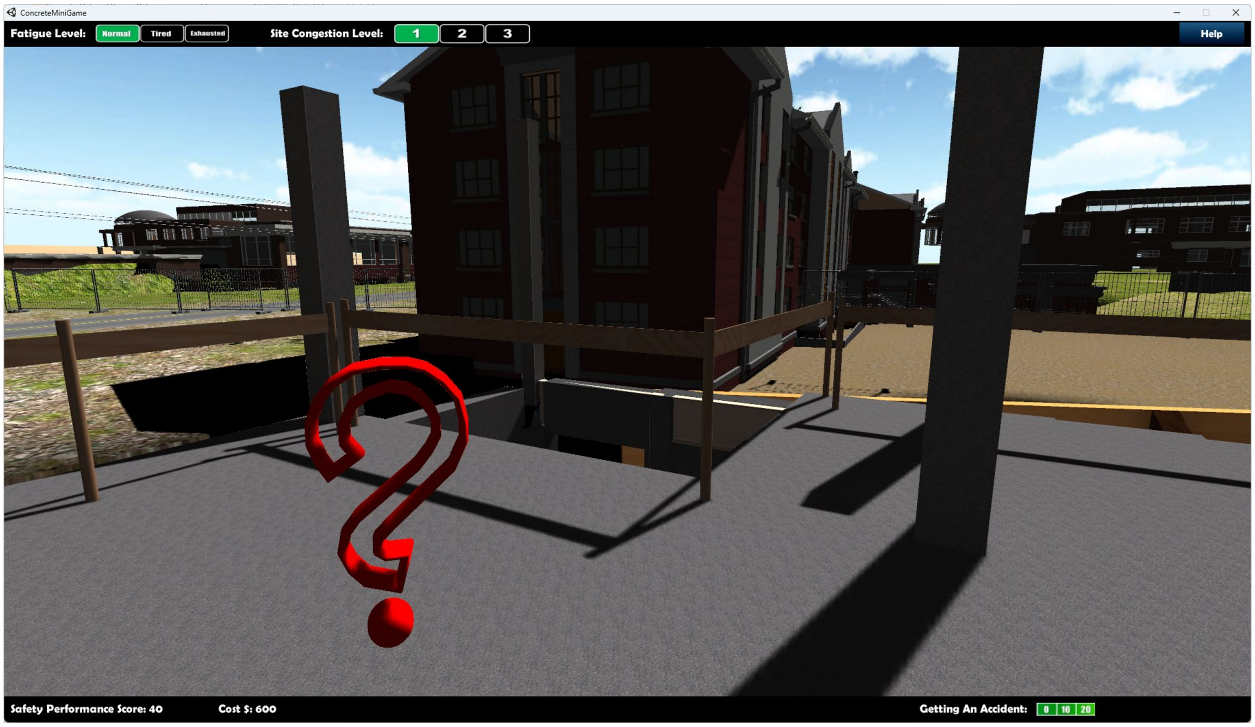

Figure 5. Example of Fall Hazards that the User of the Serious Game was Asked to Identify on the Virtual Construction Site

Students receive immediate feedback when their responses are incorrect. They were allowed repeated attempts until the correct answer was selected. The number of attempts is recorded and reflected in the safety performance score and associated penalty costs (Figure 4). Participants also receive feedback in the form of hints to help identify hazards and guidance to correct their answers. They keep navigating the virtual construction site, identifying other hazards, and responding to related questions (Figure 5). This process was used to measure participants' descriptive knowledge.

In addition to performance data, survey data were collected from the VR training participants. The survey questionnaires were developed based on the TAM. This study adapted the questionnaires from prior studies on mobile digital game-based learning [9] and construction safety and health training [4]. We also modified questionnaires used to evaluate the effectiveness of augmented technology for acquiring information on pipe assembly tasks [12] and incorporated them into this study. Four constructs in the TAM were selected for this study: perceived usefulness (PU), perceived ease of use (PEU), attitude (AT), and behavioral intention to use (BIU). Table 1 lists the research constructs and measurement items.

Demographic data and information on the participants' prior experiences with university safety courses, OSHA safety training, VR, 3D modeling, computer-aided design (CAD) software, and 3D video games were also collected. In addition, participants identified simulation factors, including sound, reflection, haptic, and animation effects, that they thought would enhance their engagement while playing the VR safety serious game. They could choose multiple items in their responses.

Table 1. Assessment Item for the Constructs in the TAM

Construct	Assessment Items	
Perceived Usefulness	Using VR Construction Safety Serious Game enables me to understand the safety and health regulations for concrete construction tasks.	PU1
	Using VR Construction Safety Serious Game enables me to understand the potential hazards in concrete construction tasks.	PU2
	Using VR Construction Safety Serious Game helps me to understand the concrete construction process.	PU3
	Using VR Construction Safety Serious Game enables me to accomplish learning correctly.	PU4
	Using VR Construction Safety Serious Game enables me to accomplish learning quickly.	PU5
	Overall, I find the VR Construction Safety Serious Game to be useful when learning about the safety regulations in the concrete construction task.	PU6
Perceived Ease of Use	It is easy to implement the VR Construction Safety Serious Game in the construction safety training.	PEU1
	It is easy to learn safety and health regulations using the VR Construction Safety Serious Game.	PEU2
	It is easy for me to find information through the VR Construction Safety Serious Game.	PEU3
	It is easy for me to learn how to use the VR Construction Safety Serious Game.	PEU4
	The process of using the VR Construction Safety Serious Game is clear and understandable.	PEU5
	I find it easy to do what I need to in the VR Construction Safety Serious Game.	PEU6
Attitude	Learning about safety through the VR Construction Safety Serious Game is a good idea.	AT1
	I feel positive toward the use of the VR Construction Safety Serious Game.	AT2
	I believe that the VR Construction Safety Serious Game helps me become more engaged in learning.	AT3
	I generally favor the use of the VR Construction Safety Serious Game for learning.	AT4
	I believe that it is a good idea for me to use this VR Construction Safety Serious Game for my future construction safety coursework or training.	AT5
Behavioral Intention to Use	I intend to frequently use the VR Construction Safety Serious Game to learn safety and health regulations.	BIU1
	I would like to participate in or experience the VR Construction Safety Serious Game in construction safety training.	BIU2
	I recommend using the VR Construction Safety Serious Game for construction safety training.	BIU3

All participants received a $10 Amazon gift card upon completion of the experiment and survey. This study was approved by the Institutional Review Board at Central Connecticut State University (Protocol #10757). In this study, participants with at least five years of industry experience were defined as the industry group, whereas those with less experience were defined as the student group. In general, five years of experience is considered indicative of professional-level expertise in the construction industry, and this criterion has been widely adopted in academic research [13]. Participants who met the industry experience criteria were classified in the industry group even if they were enrolled in an undergraduate program.

The construction industry is conservative in adopting innovative technologies [13]. Considering this, this study hypothesized that the mean scores of the research construct measurements of the TAM in the student group would be higher than those in the industry group. We assumed that the industry group would be more conservative in adopting VR technology for construction safety education and training. Data normality was evaluated using the Shapiro–Wilk test, and hypothesis testing was conducted using the Mann–Whitney U tests with an alpha level of 0.05.

Results

A total of 105 participants (64 students and 41 industry professionals) participated in the VR construction safety training experiment and responded to survey questionnaires. The average age of the student group was 21.9 years, and that of the industry group was 40.7 years. The average work experience of the student group was 1.3 years, and that of the industry group was 17.1 years (Table 2).

In the student group, the largest proportion of participants were at the junior academic level (34.4%), whereas in the industry group, the majority were graduates (75.6%). More than 80% of the participants in both groups were male. Regarding safety training, such as completing undergraduate level construction safety courses and OSHA 10-hour and 30-hour courses, 79.7% of the student group and 90.2% of the industry group responded they had experience with safety courses. Regarding VR training, more than 90% of all groups responded no prior experience with VR training.

Table 2. Demographic information

Variable	Student (N=64)	Industry Professionals (N=41)	Overall (N=105)
Gender			
Male	54 (84.4%)	36 (87.8%)	90 (85.7%)
Female	10 (15.6%)	5 (12.2%)	15 (14.3%)
Age	21.9 (2.70)	40.7 (13.74)	29.2 (12.69)
Academic Standing			
First Year	2 (3.1%)	0 (0.0%)	2 (1.9%)
Sophomore	13 (20.3%)	2 (4.9%)	15 (14.3%)
Junior	22 (34.4%)	2 (4.9%)	24 (22.9%)
Senior	16 (25.0%)	6 (14.6%)	22 (21.0%)

Graduate	11 (17.2%)	31 (75.6%)	42 (40.0%)
Safety Training Experience			
Yes	51 (79.7%)	37 (90.2%)	88 (83.8%)
No	13 (20.3%)	4 (9.8%)	17 (16.2%)
Construction Industry Experience (Years)	1.3 (1.25%)	17.1 (12.32%)	7.5 (10.91%)
Experience with VR training in academic settings			
Yes	5 (7.8%)	1 (2.4%)	99 (94.3%)
No	59 (92.2%)	40 (97.6%)	6 (5.7%)
Experience with 3D-modeling or computer aided design software			
No experience	2 (3.1%)	5 (12.2%)	7 (6.7%)
Very little experience	5 (7.8%)	10 (24.4%)	15 (14.3%)
Little experience	7 (10.9%)	8 (19.5%)	15 (14.3%)
Some experience	31 (48.4%)	6 (14.6%)	37 (35.2%)
Fair experience	18 (28.1%)	9 (22.0%)	27 (25.7%)
Extensive experience	1 (1.6%)	3 (7.3%)	4 (3.8%)
Experience with 3D video games			
No experience	10 (15.6%)	11 (26.8%)	21 (20.0%)
Very little experience	11 (17.2%)	11 (26.8%)	22 (21.05)
Little experience	11 (17.2%)	2 (4.9%)	13 (12.4%)
Some experience	16 (25.0%)	9 (22.0%)	25 (23.8%)
Fair experience	8 (12.5%)	6 (14.6%)	14(13.3%)
Extensive experience	8 (12.5%)	2 (4.9%)	10 (9.5%)

The mean scores of the measurement variables of the industry groups were generally lower than those of the student group (Table 3). However, no significant differences were found between the two groups regarding perceived usefulness (PU), perceived ease of use (PEU), attitude (AT), and behavioral intention to use (BIU). Using the Mann-Whitney U test, this study found that the average of the PEU5 (the process of using the VR Construction Safety Serious Game is clear and understandable) score was significantly different between the student and industry groups ($P<0.05$).

Table 3. Comparison of TAM Constructs Measurement Variables Between Student and Industry Participants

Construct	Measurement Variable	Students (N=64)		Industry Professionals (N= 41)		Shapiro–Wilk Test	Mann–Whitney U test
		Mean	SD	Mean	SD		
Perceived Usefulness	PU1	6.1	.09	6.0	.11	**<0.05**	0.552
	PU2	6.3	.10	6.0	.12	**<0.05**	0.110
	PU3	5.6	.13	5.1	.21	**<0.05**	0.058
	PU4	6.1	.10	5.8	.15	**<0.05**	0.062

	PU5	6.1	.13	5.9	.14	**<0.05**	0.076
	PU6	6.3	.10	6.1	.11	**<0.05**	0.074
Perceived Ease of Use	PEU1	5.8	.16	5.9	.18	**<0.05**	0.953
	PEU2	6.0	.11	6.0	.14	**<0.05**	0.872
	PEU3	5.6	.14	5.6	.16	**<0.05**	0.871
	PEU4	6.4	.08	6.1	.13	**<0.05**	0.121
	PEU5	6.4	.10	6.1	.10	**<0.05**	**<0.05**
	PEU6	6.1	.13	6.0	.14	**<0.05**	0.180
Attitude	AT1	6.5	.10	6.3	.12	**<0.05**	0.169
	AT2	6.5	.11	6.3	.13	**<0.05**	0.054
	AT3	6.4	.12	6.3	.14	**<0.05**	0.263
	AT4	6.0	.15	6.0	.14	**<0.05**	0.443
	AT5	6.2	.12	6.0	.14	**<0.05**	0.248
Behavioral Intention to Use	BIU1	5.2	.17	4.9	.21	**<0.05**	0.200
	BIU2	6.0	.14	6.0	.14	**<0.05**	0.621
	BIU3	6.2	.13	6.1	.14	**<0.05**	0.292

Table 4 presents the results of the analysis that tested the difference in the sum of the scores of the measurement variables of each construct by student and industry groups. The results indicate that the student group's mean for PU was statistically significantly higher than that of the industry group ($P<0.05$). However, no significant differences were found for the mean scores of PEU, AT, or BIU.

Table 4. Comparison Between the Mean Scores of TAM Constructs Between the Student and Industry Professional Groups

Construct	#items	Students (N=64)		Industry Professionals (N= 41)		Shapiro–Wilk Test	Mann–Whitney U test
		Mean	SD	Mean	SD		
Perceived Usefulness (PU)	6	36.5	.49	34.9	.65	**<0.05**	**<0.05**
Perceived Ease of Use (PEU)	6	36.4	.48	35.7	.65	**<0.05**	0.378
Attitude (AT)	5	31.7	.53	30.9	.58	**<0.05**	0.150
Behavioral Intention to Use (BIU)	3	17.4	.40	17.0	.42	**<0.05**	0.214

The level of engagement remained high. More than 80% of respondents in both groups reported feeling "fairly" or "very" engaged (Table 5).

Table 5. Level of Engagement Between the Student and Industry Professional Groups

Scale	Students (N=64)	Industry Professionals (N=41)	Overall (N=105)
Not at all engaged	0 (0.0%)	3 (7.3%)	3 (2.9%)
Very little engaged	2 (3.1%)	0 (0.0%)	2 (1.9%)

Little engaged	0 (0.0%)	3 (7.3%)	3 (2.9%)
Somewhat engaged	6 (9.4%)	5 (12.2%)	11 (10.5%)
Fairly engaged	28 (43.8%)	15 (36.6%)	43 (41.0%)
Very engaged	28 (43.8%)	15 (36.65)	43 (41.0%)

Further investigation was necessary to identify the factor that could improve PU among industry professionals because they reported significantly lower PU scores compared to the student group (Table 4). A regression analysis was conducted to identify the demographic factors affecting the total score of each construction item. This regression model included gender, age, academic standing, safety training experience, VR experience, and 3D modeling or CAD software experience for the industry groups.

The dependent variable was the summed scores for constructs that showed significant differences between the industry and student groups. Because the summed PU scores were not normally distributed, they were log-transformed for the analysis. Additionally, multicollinear independent variables were excluded from the model to ensure model integrity. This analysis found that participants in the industry group with no formal OSHA safety education or training and with lower engagement levels reported lower PU scores. Subsequent modeling confirmed a positive correlation between the engagement level and the PU score (Table 6).

Table 6. Regression Analysis Results To Identify The Factors Associated With The Perceived Usefulness Among Professionals

Variable	β	SE	p-value
Gender (male= 0; female = 1)	0.07	0.05	0.170
Standing (graduate = reference level)			
Sophomore	0.08	0.09	0.370
Junior	0.06	0.09	0.453
Senior	-0.12	0.06	0.036
Experience with construction safety management course or OSHA training (yes=0; no=1)	-0.12	0.059	**<0.05**
Experience with 3D-modeling or computer aided design software (yes=0; no=1)	-0.01	0.013	0.584
Experience with 3D video games (yes=0; no=1)	0.004	0.013	0.775
How engaged are you in taking part in the VR Construction Safety game (not at all engaged=1 through very engaged=6)	0.030	0.014	**<0.05**
Cons	3.469	0.0972	
R-squared	0.418		
Adj R-squared	0.272		

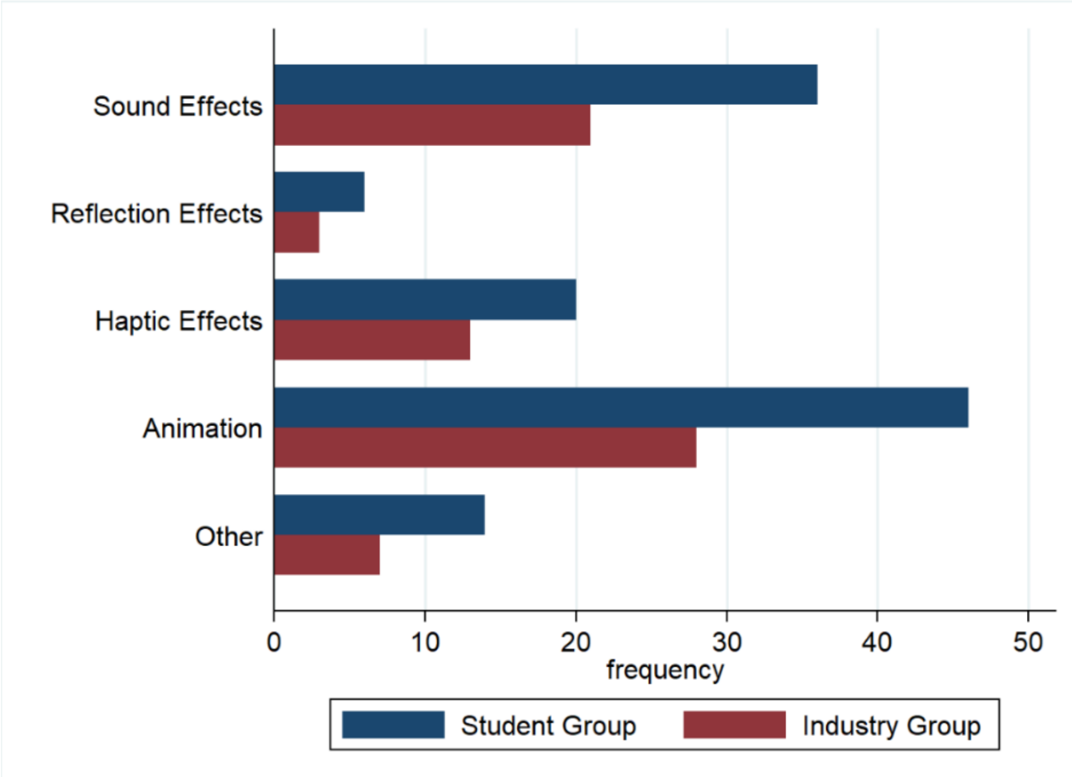

Figure 6. Preferences of Simulation Factors for Improving Engagement in the VR Training by Student and Industry Professional Groups

Regarding factors of engagement, both groups identified animation effects, such as moving construction equipment, as the most important factors (Figure 6). Sound effects, including tool-related audio cues, were ranked as the second most influential factor in the training module. Conversely, reflection effects were found to have the least impact on participant engagement.

Discussions

This study aims to bridge the existing research gap by developing a comprehensive framework for VR-based safety training grounded in pedagogical theory and evaluating its acceptance both for students and industry professionals. The results show that the developed VR serious game has the potential to be a versatile solution suitable for both students and professional applications.

Both student and industry groups identified animation effects (e.g., moving equipment) and sound effects (e.g., tool noise) as the most important factors for improving trainee engagement. These findings highlight the need for a dynamic element in the development of VR-based serious games for safety training. Static or silent environments can lead to trainees' disengagement and diminished training efficacy. In addition, VR safety training should be integrated into Bloom's taxonomy and delivered alongside formal OSHA training, rather than treated as a standalone instructional tool, thereby maximizing its perceived usefulness (PU), particularly for industry professionals.

According to Bloom's Taxonomy, lower-level learning begins with knowledge acquisition and develops into higher-level learning through application and practice. The knowledge gained from traditional lectures can be applied to the serious game, enabling students to engage in higher-level learning. To achieve this, instructors can choose between two integration methods:

- The Parallel Method: Traditional instructional materials are embedded directly within the serious game. This approach allows instructors to assess and diagnose student performance conveniently, even if the user is not yet fully proficient with the VR interface.
- The Sequential Method: This approach begins with traditional classroom teaching to establish foundational knowledge about OSHA standards and regulations in the construction industry, followed by VR-based safety training sessions where students apply their knowledge in a virtual environment.

Both methods ultimately aim to help students develop a holistic view of expected outcomes from their decisions under all constraints, situations, and selected solutions in relation to a construction process. However, based on industry professionals' feedback, the parallel method may be more effective at improving the perceived usefulness of the training in a professional context.

Students' knowledge reinforced through VR training can be further evaluated through the development of a site-specific safety plan, which serves as a course learning outcome and aligns with the accreditation requirements of the American Council for Construction Education (ACCE). Based on what they learn in the VR training, students apply higher order skills when developing their site-specific safety plans.

Limitations and Future Research

This study was limited to safety and health regulations for concrete construction tasks. Furthermore, the effectiveness of serious games in the overall CEM education remains to be verified. In the current study, the outcomes of the VR training and knowledge retention were not evaluated. In future research, the full TAM model can be further analyzed using Partial Least Squares Structural Equation Modeling (PLS-SEM). This would provide a deeper understanding of the interrelationships among PU, PEU, AT, and BIU. Future research should expand the modified TAM to assess social, organizational, and implementation factors influencing the successful adoption of VR-based safety training in CEM curricula.

Conclusions

In this study, we used the VR-based construction safety serious game developed by the first and second authors' previous research [7], which was grounded Bloom's Taxonomy. The acceptance of the VR-based serious game was evaluated among CEM students and industry professionals through the TAM framework. This study identified the specific factors affecting acceptance of the VR safety training module within the CEM curriculum. These findings have practical implications for both academia and industry, offering a roadmap fostering a safer, more informed workforce. By integrating VR into a regular safety course, students can improve their hazard recognition skills and gain a deeper understanding of the sources of hazards, major causes of injuries and fatalities, and methods of mitigating hazards. Ultimately, students will become familiar with safety regulations and best practices. The authors believe that the findings of this study contribute to the identification of the key factors necessary for the successful implementation of VR-based safety training in CEM education.

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