Virtual Learning Environments for Construction Site Safety Training

Mounsif Chetitah[1] [0000−1111−2222−3333], Florian Graesser[2,3] [1111−2222−3333−4444], and Sebastian von Mammen[3] [2222−−3333−4444−5555]

[1] University of Wuerzburg, Sanderring 02, Germany `lncs@springer.com`
http://www.springer.com/gp/computer-science/lncs
[2] ABC Institute, Rupert-Karls-University Heidelberg, Heidelberg, Germany
`{abc,lncs}@uni-heidelberg.de`

Abstract. Jobs in the construction industry count to the most dangerous occupations. Over the last years, several efforts to improve construction site safety have been made. Among those efforts were serious game approaches, which successfully taught people in the construction industry relevant knowledge about construction safety measures through the motivating and engaging context of a game. A framework based on established learning and game design theories is proposed in this thesis, to enable fast and easy creation of virtual environments for training awareness of safety hazards. A prototype has been developed with the framework. Play tests with the prototype indicated an increased awareness of safety hazards.

Keywords: First keyword · Second keyword · Another keyword.

1 Introduction

Construction sites are inherently hazardous environments, with workers frequently exposed to a multitude of risks including falls from heights, heavy machinery accidents, electrical hazards, and exposure to hazardous materials [15]. Ensuring construction safety is paramount to prevent injuries and fatalities, with the construction industry consistently ranking among the most dangerous sectors for workplace accidents [2]. Effective training is crucial for mitigating these risks, but traditional methods often involve theoretical learning or on-site training that can potentially expose workers to dangers before they are adequately prepared [7].

Serious games, which are games designed for purposes beyond entertainment, offer an innovative solution to this challenge [10]. These games simulate real-world scenarios in a controlled, virtual environment, allowing workers to learn and practice safety protocols without the associated physical risks. By engaging users through interactive and immersive experiences, serious games can enhance understanding, retention, and application of safety procedures [6]. Moreover, they offer the advantage of repeatability, allowing trainees to practice scenarios multiple times until mastery is achieved.

This paper presents a methodological approach for developing effective serious games specifically tailored for construction safety training. Our approach integrates established educational principles, such as Bloom's Taxonomy and experiential learning theory, with game design elements to create robust and engaging training solutions [1]. By leveraging this method, developers can create customized training modules that accurately simulate real-life construction environments and challenges. This approach ensures that workers can gain practical experience and improve their safety skills in a virtual setting, significantly reducing the risk of accidents on actual construction sites while also potentially decreasing training costs and increasing accessibility [11].

2 Related Work

The application of serious games in construction safety training has gained significant attention due to their potential to enhance learning experiences while eliminating real-world risks. This section reviews relevant literature on serious games for construction safety and learning-focused approaches.

Several studies have explored the use of serious games for construction safety training. Mohd et al. (2015) investigated construction workers' willingness to learn through serious games, finding generally positive attitudes towards this approach [14]. This readiness is crucial for the successful implementation of game-based learning in construction contexts. Guo et al. (2012) developed a serious game focusing on high-risk equipment such as mobile cranes, tower cranes, and excavators [7]. Their game simulated various activities from installation to operation and disassembly, allowing trainees to interact with a virtual construction site using game controllers or keyboards. The game included features like accident notifications and hazard marking, with multiplayer functionality. Mo et al. (2018) took a data-driven approach, using machine learning to analyze fatal injury cases and generate relevant VR scenarios [13]. They identified common hazardous scenarios and used the player-game model from Rabin (2010) to design training scenarios implemented in Unity 5.5. Carozza et al. (2013) introduced an "Immersive Controlled Environment (ICE)" approach, comparing it to traditional "CAVE-type" systems [3]. Their portable VR solution showed promise in providing realistic training environments without physical risks. Dawood et al. (2014) employed a "4D" approach, creating a full-scale virtual construction site that changed over time [5]. Their study revealed that as site complexity increased, trainees' ability to spot hazards decreased, mirroring real-world scenarios. Chen et al. (2013) developed "SAVES" (System for Augmented Virtuality Environment Safety), combining VR environments with real-world images of safety hazards [4]. Their research demonstrated the effectiveness of VR-based safety training in improving hazard recognition skills.

While many studies have shown the potential of serious games in construction safety training, some researchers have emphasized the importance of incorporating established learning theories for more effective instruction. Jeelani et al. (2020) created a personalized training protocol using both virtual and stereo-panoramic environments [9]. Their approach included baseline evaluation, personalized feedback, theoretical training, and guided VR sessions, highlighting the importance of individualized instruction. Jadallah et al. (2022) proposed an instructional design framework based on Bloom's Taxonomy, the 70:20:10 principle, andragogy, and Universal Design for Learning (UDL) principles [8]. This framework aims to teach construction material information, project execution functions, and pre-construction activities. Martínez-Durá et al. (2011) emphasized the importance of incorporating instructional theories in serious games to ensure learning objectives are met [12]. They also highlighted the need for effective scoring systems to motivate learners and accurately reflect progress. Peiró et al. (2020) focused on safety training for migrant workers in construction, suggesting the use of cognitive and social constructivist instructional design models alongside objectivist approaches [16]. Their work emphasized viewing trainees as active participants in the learning process rather than mere recipients of knowledge.

This review of related work demonstrates the growing interest in serious games for construction safety training and the increasing recognition of the need to incorporate robust learning theories in their design and implementation.

3 Learning Scenarios

In our serious game design approach we followed a conceptual framework composed of three components: (1) knowledge design, (2) instructional design and (3) game design. In the first stage, we define the scope of knowledge as well as concepts and procedures to convey to the learners from a knowledge expert perspective. Second, during the instructional design phase, we define a list of learning objectives and instructions aiming at conveying the knowledge specified earlier based on Revised Bloom's Taxonomy. Last, in the game design phase, we translate all the learning objectives into gameplay goals or related to gameplay goals and we define the experience for the player, the dynamics of the game and goes without saying the mechanics.

3.1 Knowledge Design

The knowledge contained in the current application is represented through the schema shown in Table 1.

3.2 Instructional Design

Learning goals were developed using Revised Bloom's Taxonomy through an iterative process. Initially, broad and intuitive ideas were outlined and then refined into sub-categories that specified how to achieve the major learning objectives. A series of scenarios were designed where players navigate a construction site,

Protective Personal Equipment (EQ)	**Dangerous Areas**
Types of EQ	**Types of dangers**
Helmets Gloves Safety glasses Protective clothing	Heights Moving objects (e.g., cranes, vehicles) Electricity
Functions of EQ	**Indicators of danger**
Protection from impact (e.g., helmets) Protection from chemicals (e.g., gloves) Eye protection (e.g., safety glasses)	Warning signs Barriers
Usage of EQ	**Navigation around dangers**
Situations requiring specific EQ Proper wearing techniques	Planning safe paths Recognizing hazardous areas Avoiding danger zones

Table 1. Concepts and facts involved in learning objectives for construction site safety.

performing tasks to progress through various levels. These paths lead players into hazardous areas, simulating high-risk situations they would face in reality.

For example, the main objective "avoiding hazards on a construction site" was broken down into "wear protective personal equipment" and "stay away from dangerous areas." The latter was subdivided into the Cognitive Process Dimensions: "remember," "understand," and "apply/create." This resulted in specific learning objectives like "recognizing the area," "understanding why it is dangerous," and "walking around it." The prototype's major learning goals include "Recognize a dangerous area," "Understand why an area is dangerous," and "Plan a path to avoid the danger zone."

3.3 Game Design

The development process began with conceptualizing a game idea, defining a target audience, and imagining the likely aesthetics. This was followed by designing dynamics to enable the desired scenarios, from which the mechanics were subsequently derived.

In this thesis, the idea focused on virtual construction sites for learning and training purposes. Inspired by provided examples, the design potentially included elements such as Sensation, Narrative, Challenge, and Discovery.

The dynamics derived from these aesthetics are immersion, creating an immersive experience by placing the player directly into the virtual environment; challenge, setting tasks that players must achieve with the possibility of failing a level if exposed to artificial dangers, and incorporating a performance aspect based on time; and discovery, designing open levels that allow players to navigate the virtual environment and find safe paths to complete their tasks. Although the narrative was considered as a dynamic where players could follow a story while performing tasks, it was deemed too specific for the framework approach and thus not included in the final design.

Main Objective: Avoid hazards on a construction site / apply safety measures			
Objective I: Wear protective personal equipment (EQ)			
	instruction	*knowledge item*	
Objective I.1:	Know the EQ		
	Objective I.1.a:	Recognize	the EQ
	Objective I.1.b:	Recall	the EQ's name
Objective I.2:	Understand how the EQ works		
	Objective I.2.a:	Classify	the type of EQ (area to protect, importance, . . .)
	Objective I.2.b:	Compare	with other EQ based on the similarities and differences
	Objective I.2.c:	Summarize	when to use the EQ
	Objective I.2.d:	Explain	why the EQ helps when worn (e.g. helmet protects from impact)
Objective I.3:	Put on the EQ		
	Objective I.3.a:	Execute	the process of putting on the EQ
	Objective I.3.b:	Execute	wear the EQ at the right time
Objective II: Stay away from dangerous areas			
	instruction	*knowledge item*	
Objective II.1:	Recognize a dangerous area		
	Objective II.1.a:	Recognize	objects that require higher attention (crane, vehicles, machines, . . .)
	Objective II.1.b:	Recall	signs or barriers that indicate danger
Objective II.2:	Understand why/how the area is dangerous		
	Objective II.2.a:	Classify	the type of danger (height, moving object, electricity, . . .)
	Objective II.2.b:	Compare	with similar dangers (e.g. falls from different heights)
	Objective II.2.c:	Summarize	when to use the EQ
	Objective II.2.d:	Explain	why the EQ helps when worn (helmet protects from impact)
Objective II.3:	Walk around the danger zone		
	Objective II.3.a:	Plan	a path that avoids potential dangers
	Objective II.3.b:	Exectute	walk the path avoiding potential dangers

Table 2. Potential learning goals in construction site scenarios.

To enable these dynamics, various mechanics were implemented. These include movement of the character, interaction with in-game objects, incentives for moving the player to specific locations, communication of instructions to the player, a system to track player progress, level selection, notifications of success, presence of dangerous areas, and a "Game Over" scenario.

These mechanics were incorporated into the prototype and are further detailed in the methodology and implementation sections.

4 Implementation

4.1 Area Marker

The framework includes two types of area markers managed by the TriggerAreaBehaviour and ProcessAreaBehaviour scripts.

The TriggerAreaBehaviour script is event-driven, activating upon player entry detected in the OnTriggerEnter method. It notifies other systems, activates or deactivates specified scripts, and ensures the trigger is player-specific. For example, it can trigger a bulldozer to drive backwards if the player gets too close. After execution, it disables itself to avoid multiple triggers.

The ProcessAreaBehaviour script is similar but requires the player to stay within the area for a set duration. It tracks time, progress, and completion state, and uses a ProgressBar to display progress. The script functions through OnTriggerEnter to activate the ProgressBar, OnTriggerExit to reset progress, and OnTriggerStay to update the progress bar and complete the task if the player remains long enough. A delay is added post-completion to display the progress bar before deactivation.

4.2 Quest System

The quest system requires several interfaces between its components. A canvas with a TextMeshPro object displays the current tasks, and the canvas must have the QuestLogCanvas and Quest scripts attached.

The Quest script manages and displays the list of sub-tasks necessary to complete the quest. It tracks sub-task statuses by subscribing to their Update events. Upon all sub-tasks' completion, the Quest script marks the quest as complete, triggers a QuestlogUpdate event, and activates a GameObject to notify players of the level's successful completion. This GameObject must be referenced in the Quest script.

Sub-task behavior is defined in the QuestSubTask script, which stores the state and description of each task. It invokes an Update event whenever the completion state changes. Specific sub-tasks extend QuestSubTask through child classes, such as QuestSubTaskReachTarget and QuestSubTaskProcessArea, interacting respectively with TriggerAreaBehaviour and ProcessAreaBehaviour. These child classes subscribe to their respective systems' events and ensure the necessary components are added in Unity.

The quest system's modular and extendable design allows tasks to exist independently of their use in the current quest. Quests can be attached to any object in a Unity scene, with the canvas logically displaying sub-task descriptions. QuestSubTask child classes can be placed on relevant game objects and referenced in the Quest.

4.3 Metrics System

The metrics system centers around a static class called MetricsManager, which other systems call upon to register events as milestones. Milestones consist of a name and timestamp, stored in the LevelMetric class that logs all milestones for a level, including the level name and start time. All LevelMetrics are stored in a MetricSaveObject, which resolves saving/loading issues that arose from using a simple list of LevelMetrics.

Data is stored between sessions using Unity's PlayerPrefs. The JsonUtility class converts the MetricSaveObject to a JSON string for storage and retrieves it for loading. Due to JsonUtility's limitations with complex data types, the MetricSaveObject class was necessary.

MetricsManager manages TextMeshPro objects to display data and variables for the current LevelMetric and MetricSaveObject. Methods handle adding milestones, saving/loading PlayerPrefs, and formatting JSON strings for readability. Metrics generation begins when a level is loaded, creating a new LevelMetric and recording milestones based on player actions.

Events creating milestones include completing a sub-task or quest, failing by injury, switching levels, and exiting the application. The current LevelMetric is added to MetricSaveObject upon quest completion, level change, or application exit. Specific edge cases, such as forced level changes due to injury, are handled by creating an injury milestone and adding it to MetricSaveObject.

During development, saving/loading PlayerPrefs occurred at application start/close, but issues with accessing PlayerPrefs locations led to adding an export functionality. This export writes metric data to local storage in a JSON file, then deletes PlayerPrefs data. The export is manually triggered by players after testing sessions. The revised approach saves and loads data when adding LevelMetrics, ensuring stability unless the application is forcefully quit.

4.4 Falling Mechanic

The falling mechanic uses the CharacterController's y-axis velocity - the speed at which it moves up or down - as an indicator to see, if the player is currently falling. Since steps or ramps could also be downward movement, a threshold is set to filter these out. As soon as this threshold is surpassed, the player is considered to be "falling". To differentiate between the start of the fall, and any point later in the fall, a boolean is set as a flag. On a new fall, the height of the ledge the player is falling from is taken by storing the player's y-coordinate. As soon as the player is no longer considered to be falling, based on its y-axis velocity, a check for that flag is done. If it is set, this means that the player was falling until the last frame. Now the flag is reset, and the current y-coordinate of the player is taken to calculate, how deep the fall was, based on the stored height of the ledge the player fell from. If the fall was deeper than the maximum tolerated height, the player will be forcefully moved to the "Game Over" level.

4.5 Vehicles

The first approach was to implement cubic interpolation to create a curve for a vehicle object to follow. But the first version did not yield enough control over the path, and a more sophisticated system would be needed. This led to finding a free Path Creator tool in the Unity store. It was capable of the behaviors required for the prototype, which were looping through a predefined path and driving from one point to another. A PathFollower script can be attached to a game object, making it move along the path. In order to start this driving script at a giving time, the PathFollower script was set to be disabled by default, and then enabled by a TriggerAreaBehaviour in their list of scripts to enable on trigger. This approach was used in the level where the player triggers a vehicle suddenly driving backwards, if they cross the road too close to the vehicle. A separated collider was attached to the vehicles other than the one used for collision. This collider was set as a trigger, and was used to indicated player-collision with a moving vehicle. A script was attached, that would forcefully load the "Game Over" level due to injury, if the player came in contact with the collider. The collider was disabled by default, and activated when the vehicle was moving.

4.6 Sound

An AudioSource component was added to the parent element of vehicles. For the sake of easily replacing the 3D model of the vehicle, the driving script and the sound were not directly attached to the vehicle's prefab. The default values of the AudioSource component were changed to loop the audio file and the spatial blend was set from 2D to 3D, enabling directional sound in VR. Min and max distance in the 3D sound settings were adjusted from 1 and 500 by default to 3 and 50 for a more natural sound perception based on the levels size.

4.7 User Interface

TThe arm menu serves as the primary interface for player interactions and information display in the virtual environment. It is attached to the player's left wrist, making it accessible like a watch. This menu comprises three Unity canvases: the main menu, the quest log, and the metrics menu. These canvases are set to world space, moving with the left controller, and feature transparent blue backgrounds.

The main menu includes buttons for exiting the application and opening the level selection menu. The level selection menu, containing buttons for each level, is positioned based on the player's current location and orientation. Button functionality is provided by the Unity XR Toolkit.

The quest log displays current tasks using the QuestLogCanvas script, which references a TextMeshPro object for styling and subscribes to the Quest script's updates. Completed tasks are visually distinguished by crossing them out and lowering their alpha value.

The metrics menu, featuring a Unity ScrollView element, retrieves data from the MetricsManager through the MetricsAccess script. It includes buttons for changing ScrollView content, resetting metric data, and exporting metrics to a text file. The menu is hidden using the AngularVisibility script, which enables or disables objects based on the alignment of the player's head and left controller.

The ProgressBar script is attached to a custom prefab to display progress in various contexts, such as time passed in a ProcessAreaMarker. It updates both float and integer representations of progress and applies this to the image component of the prefab.

Finally, the level clear window, which behaves similarly to the level selection menu, is automatically opened by the Quest script upon quest completion, displaying a message to the player.

5 Playtesting and Evaluation

5.1 Playtesting and Questionnaires

Play tests were conducted to evaluate the effectiveness of the prototype created with the framework. Players completed questionnaires featuring Likert-scale questions to provide primarily quantitative data, with one open-ended question for qualitative feedback. The goal was to assess player experience and determine if the game effectively conveyed construction safety knowledge.

5.2 Testing Environment

Tests were conducted in a 2m x 2m obstacle-free area, preferably quiet to minimize distractions.

5.3 Instructions for Testers

Players received safety instructions, information on VR handling, and guidance on using the Oculus Quest's guardian and "pass through" features. They could test while seated if needed and were encouraged to quit if they felt unwell. "Think aloud" testing was requested for immediate feedback. Remote testers received detailed written instructions.

5.4 Metrics Collection

Metrics were gathered through timestamps at events like task completion or failure. Most players completed levels in consistent times, with VR newcomers taking longer initially but improving quickly. Accidents occurred mainly in levels 4 and 6. Noteworthy behaviors, like unusual area navigation or tool finding, were also recorded.

5.5 Questionnaire Preparation

The questionnaire, based on the Likert-scale approach, included questions about system usability, VR experience, construction safety knowledge, and game mechanics. Some questions were binary, and an open-ended section allowed for additional feedback. Results were grouped by related topics for analysis.

5.6 Results

Metrics analysis focused on average completion times, deviations, task execution order, and accident causes. The questionnaire aimed to gauge opinions on task presentation, game design, and VR experience. Positive feedback on learning success and expected criticism of VR movement were noted.

19 players participated, with 15 having prior VR experience. The majority noticed visual changes in area markers, and a few experienced falls or vehicle collisions in specific levels. Detailed results and interpretations are discussed in the evaluation section.

6 Conclusion

A framework for VR-based construction safety training environments was developed using the MDA game design framework and Bloom's Taxonomy for instructional design. A prototype application with several training levels was created and playtested, with metric data and questionnaire feedback collected.

The playtest metrics indicated that most players easily navigated the prototype's levels, which increased in complexity incrementally. Players who were initially slower improved over time, suggesting they adapted well to the virtual environment, controls, and interface.

Questionnaire results showed the prototype was user-friendly and tasks were easy to solve. Even players with no prior VR experience found it accessible, though they performed slightly slower initially. Continuous movement caused motion sickness for some, highlighting a need for alternative methods to reduce this issue.

Feedback on learning effectiveness was mixed, with a slight negative trend regarding new knowledge acquisition but a positive response to understanding construction site dangers. This discrepancy may be due to the implicit nature of the learning goals. Explicit communication of these goals through text or audio prompts might enhance the learning experience.

The framework met its objectives but has room for improvement. Current tasks are simplified, limiting cognitive engagement. Introducing more complex mechanics, such as picking up and delivering objects, could expand learning opportunities. Further enhancements and adoption of affective learning theories are discussed in the Future Work section.

References

1. Arnab, S., Lim, T., Carvalho, M.B., Bellotti, F., de Freitas, S., Louchart, S., Suttie, N., Berta, R., De Gloria, A.: Mapping learning and game mechanics for serious games analysis. British Journal of Educational Technology **46**(2), 391–411 (2015)
2. Bureau of Labor Statistics: National census of fatal occupational injuries in 2022. Report, U.S. Department of Labor (2023)
3. Carozza, L., Bosché, F., Abdel-Wahab, M.: Image-based localization for an indoor vr/ar construction training system. In: Proceedings of the 13th International Conference on Construction Applications of Virtual Reality. pp. 363–372 (2013)
4. Chen, A., Golparvar-Fard, M., Kleiner, B.: Saves: A safety training augmented virtuality environment for construction hazard recognition and severity identification. Proceedings of the 13th International Conference on Construction Applications of Virtual Reality pp. 373–384 (2013)
5. Dawood, N., Miller, G., Patacas, J., Kassem, M.: Construction health and safety training: the utilisation of 4d enabled serious games. Journal of Information Technology in Construction **19**, 326–335 (2014)
6. Gao, Y., Gonzalez, V.A., Yiu, T.W.: The effectiveness of traditional tools and computer-aided technologies for health and safety training in the construction sector: A systematic review. Computers & Education **138**, 101–115 (2019)

7. Guo, H., Li, H., Chan, G., Skitmore, M.: Using game technologies to improve the safety of construction plant operations. Accident Analysis & Prevention **48**, 204–213 (2012)
8. Jadallah, H., Friedland, C., Nahmens, I., Pecquet, C.: Development of an instructional design framework for construction materials training. Journal of Construction Engineering and Management **148**(2), 04021188 (2022)
9. Jeelani, I., Han, K., Albert, A.: Development of immersive personalized training environment for construction workers. Proceedings of the 20th International Conference on Construction Applications of Virtual Reality pp. 1–10 (2020)
10. Laamarti, F., Eid, M., El Saddik, A.: An overview of serious games. International Journal of Computer Games Technology **2014** (2014)
11. Li, X., Yi, W., Chi, H.L., Wang, X., Chan, A.P.: A critical review of virtual and augmented reality (vr/ar) applications in construction safety. Automation in Construction **86**, 150–162 (2018)
12. Martínez-Durá, R.J., Arevalillo-Herráez, M., García-Fernández, I., Gamón-Giménez, M.A., Rodríguez-Cerro, A.: Serious games for health and safety training. Serious Games and Edutainment Applications pp. 107–124 (2011)
13. Mo, Y., Zhao, D., Du, J., Liu, W., Dhara, A.: Data-driven approach to scenario determination for vr-based construction safety training. Construction Research Congress pp. 431–441 (2018)
14. Mohd, N.I., Ali, K.N., Bandi, S., Ismail, F.: Exploring gamification approach in hazard identification training for malaysian construction industry. International Journal of Built Environment and Sustainability **2**(1), 53–60 (2015)
15. Occupational Safety and Health Administration: Commonly used statistics. Web resource, United States Department of Labor (2021)
16. Peiró, J.M., Nielsen, K., Latorre, F., Shepherd, R., Vignoli, M.: Safety training for migrant workers in the construction industry: A systematic review and future research agenda. Journal of Occupational Health Psychology **25**(4), 275–295 (2020)