



Immersive Safety: Revolutionizing Construction Training with Virtual Reality and Behavioral Insights

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ABSTRACT:

The construction industry is fraught with complex hazards and high accident rates, underscoring the need for more effective safety training methodologies. Traditional lecture-based approaches often fail to prepare workers for the on-site dynamic risks. This study introduces an innovative virtual reality (VR) training kit designed to immerse construction personnel in realistic, hazard-rich environments while capturing their behavioral and physiological responses. Developed using Unreal Engine 5.1, the system integrates Cognitive3D analytics for tracking user navigation, head movement, and gaze via real-time heat maps, alongside biometric monitoring through a COOSPO Heart Rate Monitor Armband HW807. The VR simulation recreates common construction hazards, including falls from heights, falling objects, improper lighting, and unsafe scaffolding, by leveraging photorealistic textures and advanced rendering techniques. A pilot study involving 10 experienced construction professionals (engineers and workers) was conducted to assess the tool's effectiveness. Participants navigated a simulated renovation site featuring 25 induced hazards, marking potential risks as they arose. Behavioral data, including navigation paths and attention distribution, were synchronized with heart rate fluctuations to provide insights into stress responses and hazard recognition patterns. Preliminary findings indicate that personalized feedback based on integrated behavioral and biometric analytics enhances hazard awareness and decision-making. These results suggest that immersive VR training can substantially complement traditional methods, offering a scalable, data-driven approach to improving construction site safety.

KEYWORDS: Lean construction, Virtual reality (VR), Safety and Risks, Workers' Training

1. INTRODUCTION

Over the past decades, many on-site accidents have occurred in the construction industry, causing fatalities and injuries (Shim et al., 2022). According to the National Work Injury, Disease, and Fatality Statistics, the construction industry had the highest fatality rate among other economic sectors in Canada in 2022, with 183 fatalities. In addition, referring to the same study, 56 out of 183 deaths occurred in Alberta, ranking it first among other Canadian provinces.

Several studies have shown that the high death rate in construction results from the nature of the construction industry, such as the complex construction procedures, uniqueness of each project, and dynamic uncertainties on site, making it one of the most unsafe environments for workers (Swuste, 2016). Therefore, it is essential for all staff working in this industry to prioritize the challenges that stop safety improvement while reducing the high rate of injuries and fatalities.

Since 1941, research has consistently indicated that unsafe labor behaviors are a leading contributor to accidents in construction (Heinrich, 1941). Worker safety and quality assurance in the construction industry have emerged as two significant issues within the industry. Haslam et al. (2005) claimed that over half of the on-site injuries can be attributed to a lack of safety consciousness and knowledge. In addition, poor safety guidance at construction sites may increase the possibility of risk exposure.

Nevertheless, despite efforts to enhance safety performance through training, the construction industry continues to have disproportionately high injury rates (Zhou, 2015). Evaluating the efficacy of various safety training modalities will aid in developing a successful training approach. Specifically, developing cutting-edge techniques to assess the effectiveness of several building-related aspects and educating employees precisely and impartially about their risk-taking tendencies at the job site would open more methodical avenues for customizing the best construction safety training programs.

Few studies have been conducted in the literature despite the potential significance of training and assessment procedures, and a comprehensive attempt to study and assess existing approaches has not yet been undertaken. Traditional safety training methods are often delivered through lectures that fail to replicate the complexities and dynamics of real-world construction processes. This can hinder workers' ability to recognize and respond to hazards effectively. Emerging technologies such as computer vision and virtual reality (VR) offer promising solutions to address these limitations.

This study addresses this gap by developing a VR-based training kit that simulates realistic construction hazards and tracks user behavior (via Cognitive3D analytics) and physiological responses (using heart rate sensors). The primary objectives are to:

- Enhance hazard awareness and decision-making among construction personnel.
- Provide personalized feedback based on real-time behavioral and biometric data.
- Improve site safety through personalized feedback on available conditions.

2. LITERATURE REVIEW

2.1 Lean and Safety

Safety and Lean principles are strongly interrelated. In Lean language, low safety measurements in a process can lead to waste generation. In addition, injuries that occur are costly not only in terms of human suffering but also in terms of worker compensation costs, lost time, lost productivity, and higher employee turnover. Therefore, it is imperative to incorporate safety into the process and production plans to achieve the projected goals of improved worker health, reduced costs, and increased value (Nahmens et al., 2009).

According to recent studies, poka-yokes helped optimize the construction process by preventing errors and avoiding hazards that might occur. Poka-yokes can prevent, eliminate, or mitigate the consequences of errors or risks (Alguirat et al., 2023). Furthermore, Larios et al. discussed the relationship between safety and lean as a positive relationship: if safety measures increase, the flow and value of the process will advance. This relationship is illustrated in Figure 1.

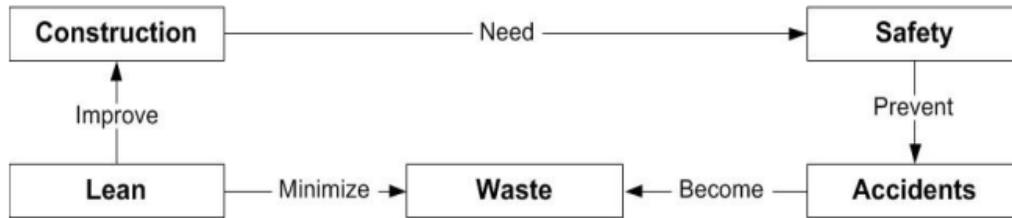


Figure 1: Relationship between Lean and safety (Larios et al., 2012)

2.2 VR Applications in Construction Projects

In the past, safety managers observed and recorded construction activities based on their work experience. Presently, the development of emerging technologies, such as computer vision, VR, AR, and many other technologies, are employed to monitor and simulate hazards on-site and monitor workers' behavior to enhance the level of safety in the construction industry (Jin et al., 2019). VR technology is based on a realistic environment and can process immediate input from dynamic situations and interact with users (Parvinen, Hamari, & Poyry, 2018). Virtual reality (VR), augmented reality (AR), and mixed reality (MR) are popular topics, and several studies have been conducted to test their different engineering aspects. The following sections preview several extended-reality studies to evaluate and measure safety and engineering metrics.

In 2019, Habibnezhad et al. used VR to determine the influence of height, self-judgment of fear, and a moving structural beam on heart rate and postural sway during a quiet stance. The study used the data gathered to determine postural sway in different scenarios. The study was a result of statistics generated by the Bureau of Labor Statistics (BLS), where, on average, three construction workers suffered fatal injuries per day. The main goal of this study was to investigate the factors affecting the postural stability of construction workers (Habibnezhad et al., 2019).

Hasanzadeh et al. (2020) conducted a study on monitoring the risk-taking behaviors of workers at construction sites by considering different safety interventions. Mixed reality is used in this study. This research referred to the construction of a roof section as a case study. Construction workers were connected to real-time head- and ankle-tracking sensors. Hasanzadeh et al. studied the reaction and response of workers throughout the process in three safety protection cases. The study concluded that workers' risk-taking behavior increased to 55% when high safety-protection measures were applied. This was illustrated by getting closer or leaning toward the edge.

Fang et al. (2014) combined real-time tracking with building information Modelling (BIM) concepts to create a virtual reality (VR) environment for training crane operators in safety measure literacy.

By referring to the previous research, several studies and applications have covered the use of VR in construction. Although numerous studies have applied VR to simulate various construction scenarios, we found no research that evaluates explicitly whether participants can independently identify safety hazards within a virtual construction site environment. To fill this gap, this study aims to develop a valuable tool to enhance the safety mapping and training stage in construction projects and notify newly hired personnel about the safety hazards surrounding them.

The tool can be used to detect workers' behavior and reactions at construction sites or manufacturing facilities for any probable safety risks. By developing this tool, several lean principles can be tackled and achieved, such as reliable technology integration, maintaining flow by eliminating or mitigating wastes, continuous reflection, and improvement by continuously updating the features of the application and adding innovative ideas to enhance the safety training procedure.

3. METHODOLOGY

The following steps were performed to achieve the research objectives: First, the team looked up and listed various safety incidents and hazards that frequently occur at construction sites. This list is fed into the model-building process to introduce it to the hazards we are interested in testing. These hazards may vary depending on the scope of application. For example, falling from heights can be a serious risk in buildings, but not a serious risk in a flat-level factory.

After gathering the required data, we developed a construction site 3D model using different design tools, the most prominent of which was the Unreal Engine 5.1 edition, produced by the Epic Games Company. The developed VR environment can be used to simulate real construction sites as realistically as possible to track and record user interaction. We focused on view scope tracking (to generate heat maps) and user navigation paths within the simulated construction site. In addition, biometric sensors such as heart-monitoring sensors are used to track the physical response of workers to risks.

Furthermore, the curated scenarios were leveraged to capture detailed behavioral and physiological responses that reflect participants' safety awareness and decision-making processes. Comprehensive data, including gaze patterns, navigation paths, and biometric signals (e.g., heart rate variations), were systematically analyzed to elucidate how participants responded to the simulated hazards. Subsequently, these insights were integrated with a Learning Management System via Cognitive3D, enabling the delivery of personalized, data-driven feedback. This approach tailors training to individual performance and facilitates continuous refinement of the VR-based training program to enhance overall construction site safety.

4. DEVELOPMENT OF VR EXPERIENCE

4.1 Platforms and Tools

The VR experience was built using Unreal Engine 5.1, which is an advanced graphics engine in terms of realism that can render and its flexibility in creating simulations with realistic graphics and excellent reproduction of natural light using ray-tracing technologies and nanites that control the meshing system in the UE5. Nanite is a high-end geometry system incorporated into Unreal Engine 5.1. It utilizes the latest rendering technology and a new internal mesh format for rendering large numbers of objects and surface details at extremely high pixel levels. The unique aspect of Nanite is its algorithm, which scans fine details without processing those that cannot be observed.

As an additional advantage, Nanite's data are decentralized and support the smooth streaming of graphics with an automatic adjustment of the levels of detail when needed (Epic, Nanite 2023). The VR application will be integrated with the Cognitive3D Developer Kit to improve the training process and monitor participant behavior. Cognitive3D integration enabled us to develop a data collection system that collects a broad spectrum of information regarding user behavior, head movement, and navigation paths within the virtual world. All this data is collected in real-time when the user is within the VR experience and then uploaded to the cloud for processing after ending the VR experience. After processing the user data, the Cognitive3D platform generates a completely reviewed scene of the different interactions used in the VR experience.

4.2 Construction Site 3D Model Development

The VR experience includes a construction site featuring various scenarios highlighting common dangers, such as hazardous materials surrounding the site, open holes filled with water, exposed scaffolds, dangerous rebar elements, and other hazards distributed throughout the area. This involves establishing the logic for hazard visibility, user interactions, and the consequences of those interactions. These scenarios were developed by reviewing the literature on construction accidents. Each scenario is tailored to reflect real-world conditions to ensure readiness for training in actual activities and experiences.

The construction site model used in this study was crafted using different 3D objects and modular components sourced online through the Unreal Engine asset library. These assets also feature realistic surface textures provided by the Quixel Megascans library, which allows us to use photorealistic surfaces that accurately replicate real construction sites, enhancing the experience for participants in this study (Quixel Megascans, 2024). Additionally, we utilized the Unreal Engine physics system to increase realism in user interactions within the VR environment by coding various interactions with the scenario. Over 200 3D construction-related elements, including cranes, unfinished buildings, piled construction materials, and other components typically found at active construction sites, were incorporated into the construction site model's development, as depicted in Figure 2.



Figure 2: The constructed construction site model for the VR experience using Unity Engine v5.1

The safety hazards and risks added to the testing site are listed in Table 1.

Table 1: Risks and hazards included in the testing model.

Risk	Description	Scale
1	Heights	Severe
2	Falling objects	Severe
3	Improper Lighting	Moderate
4	Missing stair handrails/Guards	Severe
5	Material on Floor	Moderate
6	Exposed Steel rebars	Moderate
7	Flammable Material	Severe
8	Electric Shorts	Severe
9	Flooding	Severe
10	Wet Areas	Mild
11	Faulty Ladders	Severe
12	Improper Signage	Mild - Severe

4.3 Project Simulation Settings

When developing the application, we used custom settings within an Unreal Engine to simulate realistic lighting conditions and photogrammetry scenes to deliver the most realistic experience for users. This was done by applying different changes to the default settings in Unreal Engine rendering functions to make the study participants feel that they are on a realistic construction site and have a realistic sense of understanding of the surroundings.

It is essential to be confident in the quality of the data collected from their behavior in the construction site model simulation. We changed the target hardware settings in the Unreal Engine from Mobile to Desktop to enable and expand different settings, such as bloom, separate translucency, motion blur, auto exposure, ambient occlusion, lens flares, and anti-aliasing. All previous settings affect various aspects of how the construction site model is simulated in an Unreal Engine and how the engine simulates lighting in the simulation environment.

4.4 Behavior Study Analysis

Participant behavior will be analyzed using several data collection methods facilitated by the Integration of the Cognitive3D developer kit into the backend of the VR experience architecture, which will collect different types of data, such as head movement tracking. This will allow for the generation of heat maps of eye movement, which is essential to determine where the participants are focusing during the simulations and spot if relevant hazards are noticed. This was done by using the heat map generation code to create a circular heat map that follows where the VR user is looking. As the user looks at a specific point, the color of the heat map becomes redder and more intense, as shown in Figure 4. Cognitive3D path tracking was also used to virtually track and discover how participants walked through the construction site. This was used to understand which factors influenced participants' decision-making and risk-aviation behaviors within the VR experience.

4.5 Biometric Data Integration

Heart rate sensors are the most commonly used biometric information in the VR training model integration process because they provide up-to-date information about the trainee's health status. These sensors are connected to users to provide real-time feedback on their physiological status as they go through simulations of an accurate construction site. The procedure was integrated using the Cardia application (Cardia,2024) and the integration of NumPy and SciPy modules and libraries in Python to process the pulse sensor data and rotate the information into a VR functionality.

A pulse-wave sensor measures the change in the volume of a blood vessel that occurs when the heart pumps blood from different body parts. The pulse data were acquired in real-time using a COOSPO Heart Rate Monitor Armband HW807 sensor, as shown in Figure 3, which uses Bluetooth 5.0 and is connected to the computer system that processes the VR experience. The COOSPO Heart Rate Monitor HW807 sensor was placed on the arms of the participants to accurately measure the pulse rate, as recommended by the manufacturer. The pulse sensor started collecting the pulse rate for each participant. It stores this data in real-time, as shown in Figure 3, in an Excel sheet format, with all data with timings showing the minimum and maximum pulse rates for each participant in the entire VR simulation session.

In parallel, it is equally important to ensure that data from numerous sources, including Cognitive3D analytics and pulse sensors, is cohesively combined. This is important because such synchronization allows us to link biometric and behavioral data with a corresponding event or the action of an interaction within the VR environment. We used timestamping to realize a simple data flow connection and integration.



Figure 3: The pulse rate sensor and its location on the participant's arm on the right; the captured pulse rate data via the Cardia application in real-time on the left.

4.6 Deployment and Data Collection

After completing the development of the VR experience, we started to deploy it in a virtual machine environment created in Unreal Engine, which enabled us to run the VR experience using an external GPU with the Oculus Quest direct link function, which allows us to use the Oculus Quest VR device as a viewer unit. However, the actual processing of the graphics occurs on our workstation, which has an AMD Radeon RX 6800M GPU that would perform heavy lifting to make the user experience smoother and free of delays and latency, which might cause headaches and dizziness for the users in the simulation. This approach was used because the Oculus Quest's graphic processing power could not independently handle the developed VR experience.

5. USER TRAINING, DATA COLLECTION, AND ANALYSIS

A renovation site was created to test the developed tool with 25 induced safety risks and hazards at various locations. The safety hazards and risks were of different severities, such as missing handrails and safety barriers on scaffolds, no lights on staircases, unsafe electrical connections next to flammable materials, etc.

The team experimented on 10 participants. The participants had at least three years of construction and site experience and were familiar with site safety regulations. The participants were classified as construction engineers and construction workers. The experiment began by presenting an overview of the tool and how it worked. The participants then started deploying marks (in this case, cones) on any safety hazard or risk they recognized, as shown in Figure 4.

As the participants were locating hazards and walking through the site, the team monitored the participants' view and areas of concentration through the simultaneously generated real-time heat map, as shown in Figure 4. At the same time, the team was checking every hazard that the participant located and marked successfully. We also analyzed the users' movement and attention patterns, which would give us insight to provide more personalized feedback for the participants on improving their hazard awareness on construction sites and avoiding potential dangers in the future. After finishing the experiment, the participants were asked to complete a short survey to reflect on the process and provide their comments and feedback. After that, we discussed the results together to spread awareness of any undetected hazards.



Figure 4: Real-time tracking and monitoring of participants' views and concentration.

Among the 10 experiments performed, 8 participants successfully detected the intended 25 risks we implemented in the model. On the other hand, one participant detected 21 out of 25 risks, and another participant detected 22 out of 25 risks. Table 2 shows the number of risks detected per participant. In addition, the heart rate monitor helped the team trace the participants' behavior and stress levels when experiencing the risks. For example, standing next to heights without a safety barrier results in an increased heart rate. Figure 5 shows that 80% of participants experienced a heart rate of more than 100 bpm when they got near hazards.

Table 2: Number of risks detected by each participant.

Participant	Engineer/Worker	Risks Detected (?/25)
1	Engineer	25
2	Engineer	25
3	Engineer	22
4	Worker	21
5	Worker	25
6	Worker	25
7	Engineer	25
8	Worker	25
9	Engineer	25
10	Worker	25

After analyzing the surveys, we found that some participants offered additional safety measures that could be applied in addition to the 25 testing points induced by the team to increase safety measures. For example, one participant mentioned that the barrier on floor 2 was low, and it is considered a risk of falling. Another participant stated that the lighting in one of the rooms is dimmed, and it should be brighter to avoid tripping.

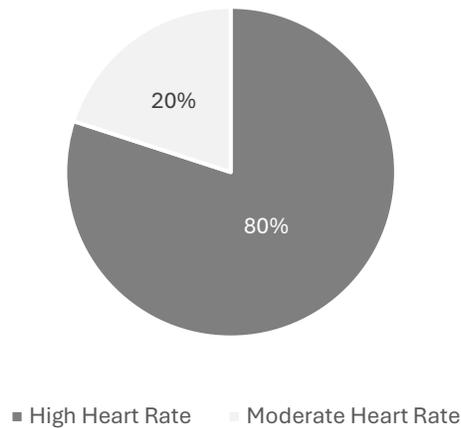


Figure 5: Distribution of participants experiencing a high heart rate when exposed to hazards

6. CONCLUSION AND RECOMMENDATIONS

This study was undertaken to create a VR training kit to boost construction workers' safety awareness. VR excursion emulates a realistic construction site situation with many potential hazards. The system follows the user's behavior through heat maps, route tracking, and physical responses of the user by using a heart rate monitor. This permits deeper insight into the level and types of user stress and attention concentration that occur when hazards occur. The conclusions of different studies emphasize that this technology could be an excellent resource for construction safety training.

The proposed project has been successfully developed and verified. The tool can be used to train new personnel and engineers on on-site risks, improve site safety, and monitor personnel's behavior when they are close to hazards. However, the study can be held forward for better and more reliable outcomes. Although the initial test involved only 10 participants (a majority of engineers), this pilot study provides preliminary insights. Future work will expand the sample to include more workers and foremen to ensure broader representativeness. To sum up, VR can be a powerful supplement to conventional training approaches by securely and hands-on exposing learners to virtual scenarios. This can lead to more effective safety results following exposure to actual construction sites in the natural environment.

Future research could be oriented toward user evaluation of the VR training program to determine whether it can raise the level of recognition of hazards and decision-making. In addition, skilled persons can search for AI applications by creating personalized feedback in VR simulators. In general, VR technology can change the way workers are trained for safety purposes in construction, using scenarios and techniques that are engaging, fully immersive, and data-driven.

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