Sabek, M., Ammar, B. A., Gonzalez, V., and Hamzeh, F. (2026). Immersive Safety: Revolutionizing Construction Training with Virtual Reality and Behavioral Insights. *Lean Construction Journal* 2026 Special Issue CRC-CSCE pp 96-113 https://doi.org/10.60164/zsjnc2rvu
(Submitted 10Jan2026; Accepted 10Sep2026)
www.leanconstructionjournal.org

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

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Abstract

Questions: Q1: How can we reduce safety incidents at construction sites using VR Technologies? Q2: How can we make the training and hiring process easier for construction workers?

Purpose: The purpose of this paper is to introduce and evaluate an immersive virtual reality training kit that prepares construction personnel for static risks by simulating realistic, hazard-rich environments.

Research Method: VR model environment development, integration of analytics with biometrics, pilot study, and data analysis

Findings: This paper documents that using behavioral and biometric analytics enhances workers' hazard awareness before allocation to a construction site and managers/superintendents' decision-making when allocating resources.

Limitations: L1: The developed VR model was based solely on static hazards. L2: As a proof-of-concept for the proposed framework, this study utilized a pilot cohort of 10 experienced professionals. While this sample size limits broad statistical generalization, it enables a high-resolution analysis of complex, multimodal data streams (biometric, behavioral, and navigational) to validate the system's technical and operational efficacy.

Implications: Dynamic hazards, such as moving cranes or trucks, can be added based on the site environment. A real case study will be considered to demonstrate the application of the tool for future research

Value for authors: This paper introduces the reader to the framework we followed and provides the industry with a training kit for resource allocation.

Keywords: Lean construction, Virtual reality (VR), Safety and Risks, Workers’ Training
Paper type: Full Paper

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Introduction

Over the past decades, the construction industry has been plagued by on-site accidents resulting in fatalities and injuries (Shim et al. 2022). Despite technological advancements, construction had the highest fatality rate among economic sectors in Canada in 2022, recording 183 fatalities according to National Work Injury, Disease, and Fatality Statistics. Of these, 56 deaths occurred in Alberta, ranking it highest among Canadian provinces.

These statistics highlight a persistent, critical failure in current safety management systems; therefore, we need to investigate the numbers and determine how we can reduce safety incidents on construction sites. Several studies have shown that the high death rate in construction results from the nature of the industry, including complex construction procedures, the uniqueness of each project, and dynamic on-site uncertainties, making it one of the most unsafe environments for workers (Swuste, 2016). However, the human element remains the critical variable. Therefore, it is essential for all staff working in this industry to prioritize the challenges that hinder safety improvements while reducing the high rates of injuries and fatalities.

Since 1941, research has consistently shown that unsafe labor behaviors are a leading contributor to construction accidents (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 et al. 2015). Evaluating the efficacy of various safety training modalities will help develop a successful training approach. Specifically, developing cutting-edge techniques to assess the effectiveness of various building-related aspects and educating employees precisely and impartially about their risk-taking behavior at the job site would open more systematic avenues for tailoring the most effective 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.

Within the concept of Lean Construction, safety incidents represent a critical form of waste (*muda*) (Nahmens and Ikuma, 2009). Beyond the unacceptable human cost, accidents inherently disrupt production flow, leading to significant project delays and extensive rework (Demirkesen, 2019). The high injury and accident rates across the industry indicate that there is a problem in the traditional safety training techniques, as they are not serving their goal in mitigating the risks. Consequently, these conventional training methods often function as non-value-adding activities consuming valuable time and resources without reliably delivering competent, safe workers. To uphold Lean principles, the industry must transition toward more effective techniques that eliminate the waste inherent in ineffective training and measurably improve the quality of the safety preparation process.

Emerging technologies offer promising solutions to address these limitations aligned with lean goals. This study addresses this gap by introducing a VR-based training kit that simulates realistic construction hazards and tracks user behavior via Cognitive3D analytics (CognitiveVR, 2024) 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.

Literature Review

Lean and Safety

Safety and Lean Construction principles are intrinsically connected, as Lean philosophy seeks to eliminate all forms of waste, including those generated by unsafe working conditions and accidents (Howell et al., 2002; Nahmens & Ikuma, 2009). From a Lean perspective, poor safety performance directly leads to waste through injuries, production interruptions, rework, schedule delays, and increased workflow variability (Howell et al., 2002). Beyond the unacceptable human cost, construction injuries result in significant financial losses, including workers' compensation costs, lost workdays, reduced productivity, and increased employee turnover, all of which undermine value generation in Lean systems (Nahmens & Ikuma, 2009; Gambatese et al., 2017).

Multiple studies have demonstrated that Lean construction practices, such as standardization, systematic workflow planning, and reduced material congestion, contribute to safer work environments by improving visibility, orderliness, and predictability on site (Nahmens & Ikuma, 2009; Antillón et al., 2011). Antillón et al. (2011) established a strong association between Lean tools, including the Last Planner System, autonomation (jidoka), and standardization and safety management practices, concluding that Lean-based planning processes can proactively support safety objectives and reduce exposure to hazards. Similarly, Lean concepts such as "stop-the-line" mechanisms empower workers to intervene when unsafe conditions arise, reinforcing worker engagement and situational awareness (Antillón et al., 2011; Gambatese & Pestana, 2014). In addition, Eltahan et al. (2024) proposed a framework for using Wearable Cognitive Assistant Devices (WCADs) to enhance the safety and well-being of workers. Shehab et al. (2026) developed a framework that matches task complexity and cognitive load to workers' cognitive abilities to reduce incidents and improve productivity. Salhab et al. (2024) proposed a framework for workspace management to minimize congestion and conflicts on construction sites, thereby reducing incidents and improving quality.

Safety has increasingly been recognized as a critical performance metric within production management, alongside time, cost, and quality, reflecting its central role in stabilizing workflows and reducing uncertainty (Hosseini et al., 2011). From this viewpoint, safety-related incidents are classified as a distinct form of waste, as they introduce unplanned variability that disrupts production flow and undermines Lean objectives (Howell et al., 2002; Hosseini et al., 2011). Empirical evidence further suggests that implementing Lean tools supports safety programs by encouraging safe behaviors, enhancing communication efficiency, and reducing injury rates at the project level (Gambatese et al., 2017).

Error-proofing mechanisms, such as poka-yokes, have also been shown to strengthen the integration of Lean and safety by preventing hazardous actions and minimizing the likelihood or severity of errors before they occur (Alguirat et al., 2023). Poka-yokes contribute to safer construction processes by either eliminating unsafe actions entirely or mitigating their consequences, thereby supporting continuous flow and value creation (Alguirat et al., 2023; Larios et al., 2020). Recent studies emphasize that improvements in safety performance positively reinforce Lean outcomes, as higher safety levels enhance process flow, operational stability, and value delivery across construction activities (Larios et al., 2020; Gambatese et al., 2016).

Despite these demonstrated benefits, a persistent gap remains between Lean implementation and its direct influence on worker behavior, indicating the need for targeted interventions that address safety awareness and decision-making at the individual level (Gambatese et al., 2017; Zhou et al., 2015). Addressing this gap is essential to fully realizing the synergistic potential of Lean Construction and safety management, particularly through data-driven, behavior-focused approaches that align with Lean principles of continuous improvement and waste elimination (Antillón et al., 2011; Gambatese & Pestana, 2014).

Figure 1. Relationship between Lean and Safety

VR Applications in Construction Projects

In the past, safety managers observed and recorded construction activities based on their work experience. Presently, emerging technologies, such as computer vision, VR, AR, and others, are employed to monitor and simulate on-site hazards and to monitor workers' behavior to enhance 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 et al, 2018). Virtual reality (VR), augmented reality (AR), and mixed reality (MR) are popular topics, and several studies have examined their engineering aspects. The following section previews 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 gathered data to determine postural sway across 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 to monitor workers' risk-taking behaviors at construction sites, 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. Moreover, Lui et al. (2025) developed a Digital twin framework that uses VR for construction fire hazard training.

According to the previous research, several studies and applications have covered the use of VR in construction. Although numerous studies have used VR to simulate various construction scenarios, we found no research that explicitly evaluates 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 safety mapping and training during construction projects and to 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 to identify potential safety risks. By developing this tool, several lean principles can be implemented, such as reliable technology integration, maintaining flow by eliminating or mitigating waste, continuous reflection, and improvement through continuous updates to the application and the addition of innovative ideas to enhance the safety training procedure.

Methodology

The design science research (DSR) was used as the methodology for this study. According to Hevner et al (2004), The 3 main guidelines for a DSR methodology are: (1) Problem Identification, (2) Solution Development or Designing/ developing the artifact, and (3) Solution Evaluation. The problem was identified based on the gap in both literature and practice. Based on that, we designed a framework to address the problem and mitigate the risks on construction sites. Following up, an experiment was set to test and validate the framework. Figure 2 illustrates the systematic application of this DSR framework within the context of our research, mapping the transition from identifying critical safety gaps to the development and validation of the immersive VR training kit. As shown in the framework, the process begins with identifying the limitations of traditional safety training and moves through an iterative cycle of artifact creation and empirical testing.

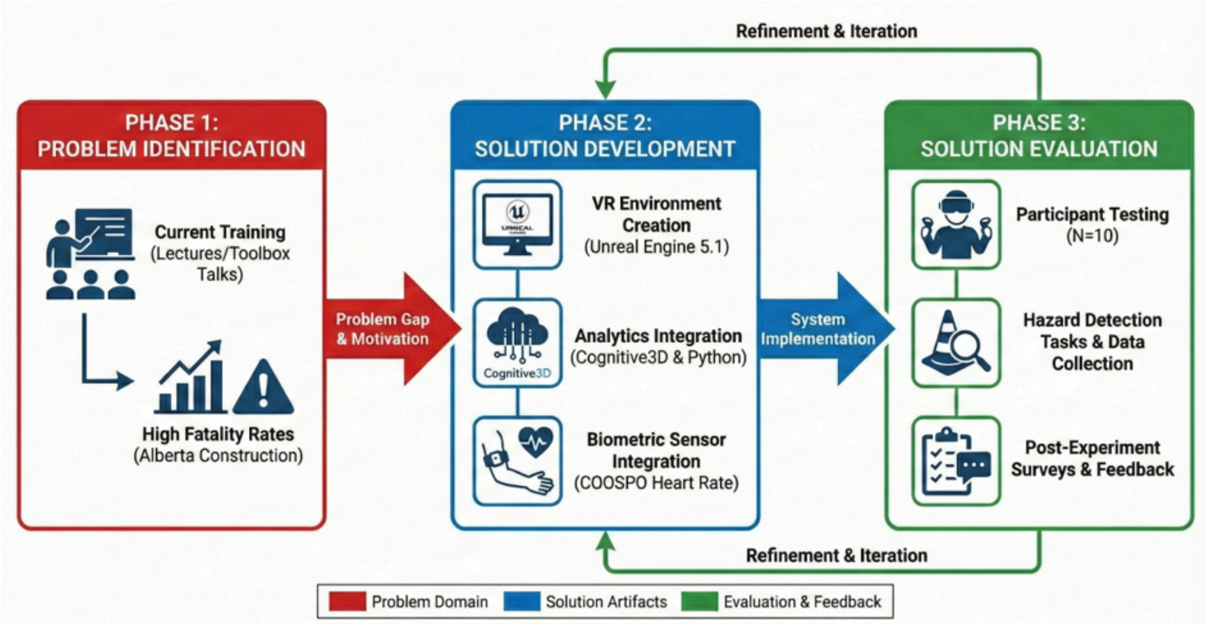

Figure 2. Design Science Research (DSR) Methodology Applied in Immersive Safety Training

Problem Identification

Despite sustained efforts to improve construction safety through regulations and conventional training programs, the industry continues to experience unacceptably high rates of injuries and fatalities. From a Lean Construction perspective, this persistent safety underperformance indicates a systemic problem rooted in ineffective processes rather than isolated incidents. Traditional safety training methods, typically delivered through classroom lectures, toolbox talks, and static visual material,s are largely generic, passive, and detached from the dynamic and hazardous conditions of real construction environments. As a result, they fail to adequately prepare workers to recognize hazards, make timely decisions, and respond appropriately under pressure. Moreover, these methods lack objective mechanisms to evaluate individual risk-taking behavior, situational awareness, and stress responses, making it difficult to assess training effectiveness or provide targeted feedback. This misalignment between training content, worker behavior, and real site conditions constitutes a significant form of waste, as time and resources are invested without reliably producing safer work practices. Consequently, there is a critical need to identify and address the shortcomings of existing safety training approaches by developing data-driven, behavior-focused methods that align with Lean principles and support continuous safety improvement

Solution Development

The following steps were taken to achieve the research objectives: First, the team reviewed 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 various design tools, the most prominent of which was Unreal Engine 5.1, produced by Epic Games. 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.

Figure 3 illustrates the overall system architecture and data flow of the Digital Eye training kit, showing how hardware components, software processing layers, cloud-based analytics, and user feedback modules are integrated to deliver a comprehensive safety training experience.

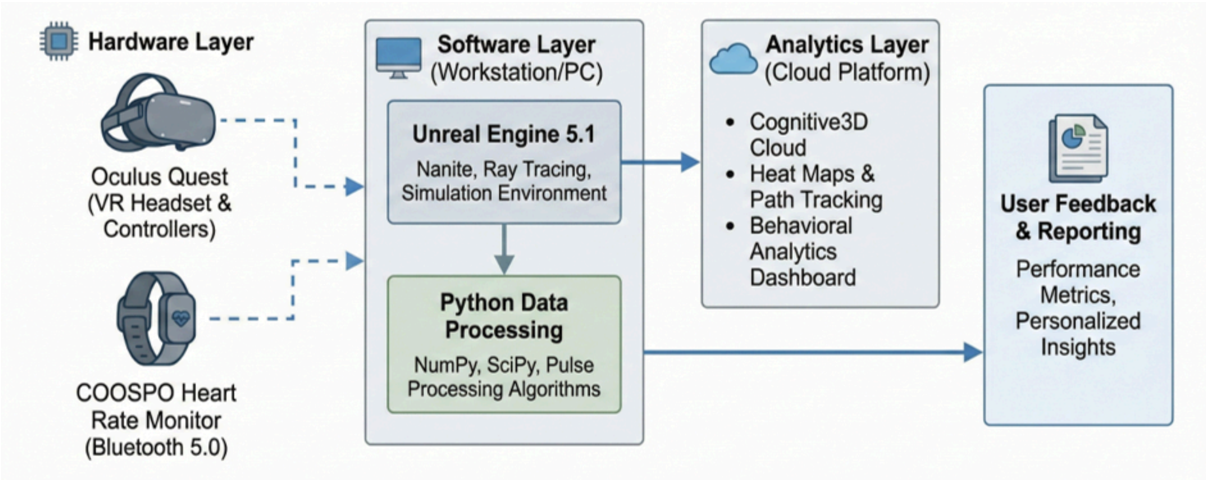

Figure 3. Digital Eye System Architecture & Data Flow

Solution Evaluation

To validate the utility of the proposed framework and the responsiveness of the biometric integration, a purposive pilot cohort of 10 participants was selected. This sample size was chosen to align with the Design Science Research objective of artifact validation, focusing on the depth of interaction data per participant rather than broad statistical inference. The cohort comprised experienced practitioners (construction engineers and workers) capable of providing expert feedback on the realism of the simulated hazards. We gave each participant a short questionnaire to complete regarding their occupation, domain, and years of experience on construction sites. Then the experiment was conducted. The participant's biometrics and a video of his behavior on the site were saved for analysis.

Model Development

Risks Identification

Each construction site or project is unique; consequently, its safety risks vary depending on the site conditions, status, and characteristics. The first step in our framework was to identify all types of hazards commonly found on construction sites. Canada Safety Training Center (CSTC) listed 10 of the most common hazards on construction sites. Table 1 shows the hazards with their severity and causes:

Table 1: Most common hazards in construction sites (CSTC, 2015)

Risk	Description	Scale Range	Causes	Safety Measures
1	Falling from Heights	Severe	perform tasks on elevated surfaces such as scaffolds, ladders, or rooftops	Guardrails, safety harnesses, safety nets
2	Electrical Hazards	Severe	exposed wires, faulty equipment, and improper grounding	Insulated tools, appropriate personal protective equipment (PPE), lockout/tagout procedures, electrical safety practices
3	Struck By and Caught Between Hazards	Moderate to Severe	hit by moving objects, caught between machinery and structures	proper signage, designate pedestrian pathways, provide barriers to separate workers from moving machinery
4	Hazardous Materials Exposure	Mild to Severe	hazardous materials such as chemicals, asbestos, and lead	hazard symbols, labels, and safe handling practices
5	Confined Spaces and Excavation Dangers	Severe	inadequate ventilation, unstable soil, improper shoring	gas detectors and ventilation systems, Adequate signage, barricades, and hazard communication
6	Fire and Explosion Hazards	Severe	use of flammable materials, Welding, Cutting	proper storage of flammable materials, keeping fire extinguishers accessible, Clear emergency Evacuation plan
7	Manual Handling	Mild to Moderate	lifting, carrying, and moving heavy objects	proper lifting techniques, Providing mechanical aids

Risk	Description	Scale Range	Causes	Safety Measures
8	Exposed Sharp Items	Moderate to severe	Exposed Steel Bars, improper signage	Proper signage, guardrails, proper training, lighting
9	Flooding/ Wet Areas	Mild to Severe	Leakage	Proper signage, guardrails around ponds, Emergency evacuation plan in case of flooding, proper communication
10	Noise	Mild to Moderate	equipment, machinery, and tools	engineering controls, administrative policies, personal protective equipment (PPE), safety training

Construction Site Development

The VR experience was built using Unreal Engine 5.1, an advanced graphics engine selected for its photorealistic rendering capabilities, flexibility in creating complex simulations, and excellent reproduction of natural light through ray-tracing technologies and nanites that control the meshing system in 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.

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 4.

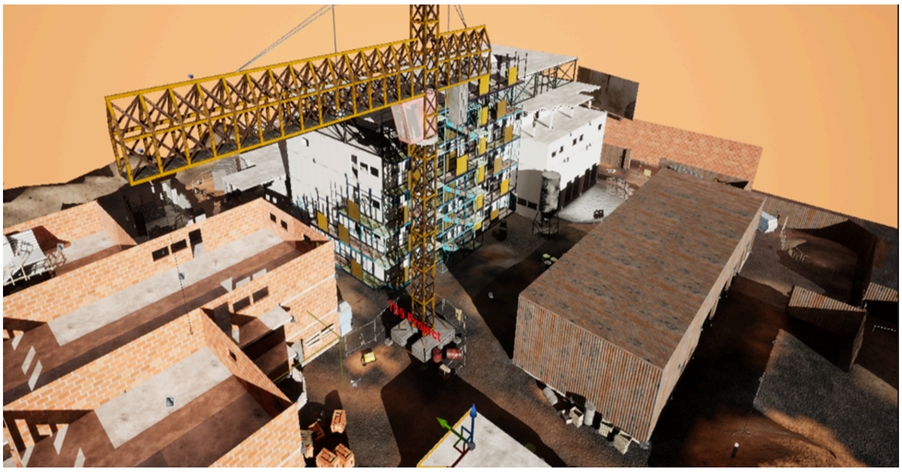

Figure 4. The Constructed Construction Site Model for the VR Experience Using Unreal Engine v5.1

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.

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 6. 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-avoidant behaviors within the VR experience. 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 graphics processing power could not handle the developed VR experience independently.

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 NumPy and SciPy modules and libraries in Python to process pulse sensor data and integrate the information into 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 5, 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 5, 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 5. The pulse rate sensor and its location on the participant's arm on the left; the captured pulse rate data via the Cardia application in real-time on the right.

Experimental Application and Results

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 performed the experiment on 10 participants. We asked them about their occupations and years of experience on the construction site. We also asked them whether they had participated in safety training tutorials or classes. 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 VR tour then started at point zero, which is the starting point. We asked the participants to follow a planned trajectory where we intentionally added the risks and hazards. After that, they started deploying marks (in this case, cones) on any safety hazard or risk they recognized, as shown in Figure 6.

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 6. At the same time, the team was checking every hazard that the participant had 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.

Figure 6. Real-time Tracking and Monitoring of Participants' Views and Concentration.

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.The team analyzed the results and presented them in tables and figures. Table 2 shows the number of risks successfully detected by the participants.

Table 2: Number of risks detected by each participant.

Participant	Engineer/Worker	Risks Detected (out of 25)	Risks Detected(%)
1	Engineer	25	100%
2	Engineer	25	100%
3	Engineer	22	88%
4	Worker	21	84%
5	Worker	25	100%
6	Worker	25	100%
7	Engineer	25	100%
8	Worker	25	100%
9	Engineer	25	100%
10	Worker	25	100%

Discussion

The primary objective of the experimental application was to verify the system's capacity to capture, synchronize, and interpret physiological and behavioral data in real-time. The results from the pilot cohort confirm the framework's sensitivity: distinct physiological arousal patterns were successfully recorded and correlated with specific hazard interactions. While the sample size precludes population-level generalizations, the consistent alignment between hazard exposure and heart rate variability (HRV) across the majority of the cohort demonstrates the technical validity of the proposed "Digital Eye" architecture. For instance, the system successfully differentiated between routine navigation and high-risk events.

Based on the results presented in the previous section, eight out of ten participants successfully detected all 25 introduced risks and hazards. The remaining two participants identified 21 and 22 hazards, respectively. The relationship between participants' performance and their prior construction experience and safety training was examined. All participants reported having received safety training before accessing construction sites. Despite this, not all hazards were detected, indicating that traditional safety training alone may be insufficient to adequately prepare personnel for on-site conditions. In contrast, immersing workers or engineers in realistic site scenarios enables them to experience and recognize actual hazards they are likely to encounter during construction operations.

Physiological measurements, particularly heart rate responses, revealed distinct patterns across different hazard scenarios. High-risk situations were associated with elevated physiological arousal, indicating increased cognitive load and stress. The heart rate monitor enabled the research team to trace participants' stress levels and behavioral responses when exposed to hazardous conditions. For instance, standing near heights without safety barriers resulted in a noticeable increase in heart rate.

Figure 7 presents an example data synchronization timeline from Participant 3's session, demonstrating the correlation between physiological arousal and specific hazard encounters. The timeline shows distinct heart rate spikes exceeding the elevated arousal threshold (100 BPM) when the participant gazed at exposed rebar, approached an unprotected edge, and passed under a suspended load. Conversely, lower heart rates were observed during routine navigation and safety checklist completion. As illustrated in Figure 8, approximately 80% of participants experienced heart rates exceeding 100 beats per minute when approaching hazards. Elevated heart rate is a commonly used indicator of stress and can support management decisions related to resource allocation, task assignment, and targeted training, particularly for hazards associated with heights or confined spaces. Elevated stress levels may also contribute to errors and reduced production efficiency, thereby negatively affecting workflow stability.

In addition, gaze heat map analysis provided further insight into participants' hazard perception. The results indicated that longer gaze durations were generally associated with higher-risk hazards, suggesting increased cognitive engagement and perceived severity. These findings reinforce the value of combining behavioral and physiological data to better understand how workers interact with safety-critical environments.

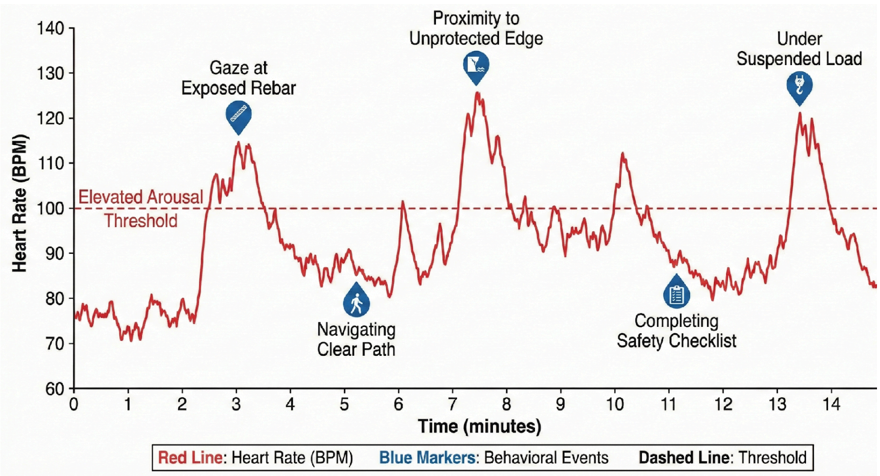

Figure 7. Data Synchronization Timeline - Participant 3 Session (Physiological & Behavioral Correlation)

Finally, the post-experiment feedback survey provided valuable insights into the effectiveness and usability of the proposed training tool, supporting its continuous improvement. Several participants also offered recommendations related to site conditions and identified three additional elements that could pose risks to on-site personnel. For example, one participant noted that the protective barrier on the second floor was insufficient in height, presenting an increased risk of falling. Another participant highlighted that the lighting conditions in one of the rooms were inadequate and should be improved to reduce the risk of tripping hazards. This feedback-driven approach enables continuous improvement not only of the training system but also of site safety practices, aligning with Lean principles of learning, waste reduction, and ongoing process optimization.

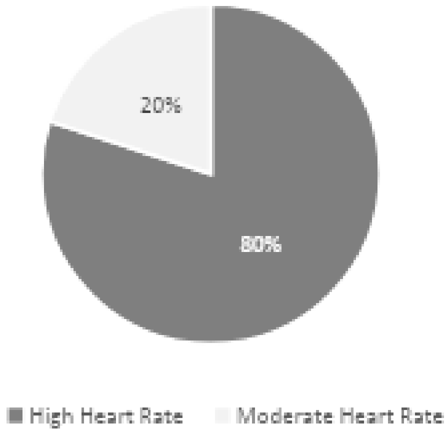

Figure 8. Distribution of Participants Experiencing a High Heart Rate When Exposed to Hazards

Conclusion and Recommendations

This study set out to address persistent shortcomings in construction safety training by developing and evaluating an immersive, data-driven virtual reality (VR) framework aligned with Lean Construction principles. Specifically, the research aimed to enhance hazard awareness and decision-making, provide personalized feedback using behavioral and physiological data, and support improvements in site safety through data-informed insights. The findings confirm that these objectives were successfully achieved.

First, the results demonstrate that the proposed VR-based training environment effectively enhanced hazard awareness and decision-making among construction personnel. Despite all participants having prior exposure to conventional safety training, some participants were unable to accurately identify all introduced hazards within the experiment. This indicates that immersive, scenario-based training better prepares workers to recognize and respond to dynamic safety risks compared to traditional, passive training methods.

Second, integrating behavioral analytics and physiological monitoring enabled the delivery of personalized, objective feedback tailored to individual performance. Gaze heat maps and navigation paths provided insights into participants' attention patterns, while heart rate responses revealed stress levels associated with high-risk scenarios. Together, these data streams allowed for the identification of individual risk sensitivities such as exposure to heights or confined spaces, thereby supporting targeted training interventions and informed task allocation.

Third, the study demonstrated how the proposed framework can contribute to improved site safety conditions. Participant feedback and post-experiment discussions led to the identification of additional site-specific hazards, highlighting the framework's potential to support proactive safety management and continuous improvement. This capability aligns with Lean principles by reducing safety-related waste, minimizing variability in worker behavior, and stabilizing production flow.

Future research can further extend the outcomes of this study in several directions. First, the current implementation of the proposed tool primarily focuses on identifying static hazards, while dynamic risks such as moving vehicles, trucks, or forklifts were not explicitly modeled. Incorporating time-dependent and moving hazards into future virtual environments would enable a more realistic representation of construction sites and support a deeper evaluation of workers' situational awareness and responses to dynamic risk conditions. In addition, while heart rate monitoring provided valuable insights into participants' physiological arousal, future studies could integrate more advanced electroencephalography (EEG) techniques to capture detailed cognitive and neural responses associated with hazard perception, attention, and mental workload.

Combining EEG data with gaze tracking, behavioral observations, and physiological measures would allow for a more comprehensive understanding of how workers cognitively process safety-critical situations. Finally, the pilot study validated the computational and operational feasibility of the framework. The integration of gaze tracking with real-time biometric monitoring was shown to be robust, successfully identifying stress markers in experienced professionals. While future research should expand the participant pool to establish statistical norms for the industry, the current study establishes the Digital Eye training kit as a functional, validated artifact ready for broader deployment and testing.

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