A Methodology for Developing Immersive Virtual Reality (VR) Training Environments to Enhance Safety and Health in Work at Height (VIRTRON)

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Abstract. Work at height activities continue to be a leading cause of fatalities in the construction industry; therefore, justifying the need for more effective safety and health training approaches. Conventional training methods often lack experiential realism, limiting workers' hazard awareness and risk recognition capabilities. Immersive Virtual Reality (VR) has emerged as a promising alternative to address these limitations. This paper presents a structured research methodology for the development of immersive VR-based safety training modules within the VIRTRON system, aimed at enhancing construction workers' safety performance during work at height activities. A mixed-methods research approach is adopted to ensure methodological robustness. The development process is organised into three phases. Phase 1 involves a questionnaire survey with safety and health officers to identify the most frequent work at height accidents and the scenarios contributing to their occurrence. Phase 2 consists of focus group discussions (FGD) with domain experts to translate the survey findings into designing a realistic VR training scenario and to plan the technical development of the system. Phase 3 focuses on the development of the VIRTRON system. Once developed, the VITRON will proceed to phase 4, where a user acceptance test (UAT) will be conducted to evaluate system usability and user acceptance. Thus, this paper validates the methodology for the development of an immersive VR-based safety training module within the VIRTRON system. The proposed methodology is hoped to provide a replicable and evidence based reference for future VR safety training development in construction work at height contexts.

Keywords: Immersive Virtual Reality; Construction Safety; Work at Height; Training Methodology

1 Introduction

The construction industry continues to record some of the highest rates of occupational injuries and fatalities worldwide. Although there have been improvements in safety regulations, technological advancements, and regulatory enforcement, the construction activities remain hazardous compared to any other industrial sector [1, 2] Among the various accident categories, falls from height consistently have been said to be one of the leading causes of severe injuries and fatalities in construction projects across both developed and developing countries [3, 4].

Work at height incidents are particularly prevalent in construction tasks such as scaffolding operations, roof installation, elevated platform work, and ladder usage. These activities involve complex physical environments and dynamic risk conditions that require workers to maintain high levels of situational awareness and hazard recognition. In Malaysia, work at height incidents continue to contribute significantly to construction-related fatalities, highlighting the need for more effective safety training strategies. The traditional construction safety training methods typically rely on classroom lectures, safety briefings, and regulatory compliance sessions. Whilst such approaches are considered to be useful for communicating procedural knowledge and safety regulations, the training methods often fail to improve real-time hazard recognition capabilities [5, 6]. Research has shown that passive learning environments provide limited opportunities for workers to experience realistic hazards or practice safety decision-making in dynamic situations [7, 8]. Consequently, a gap often exists between safety knowledge acquired during training and the behavioural responses required in real construction environments.

Immersive VR has been suggested as a technology tool that enables the simulation of hazardous construction scenarios within controlled virtual environments, allowing workers to experience risk situations without exposure to real physical danger. Immersive VR systems utilise head-mounted displays, motion-tracking sensors, and interactive three-dimensional environments to create a strong sense of presence, defined as the psychological perception of "being there" within a simulated environment [9, 10]. Through the interactive simulations, VR can support experiential learning processes that enhance hazard recognition, situational awareness, and risk perception. VR-based safety training can also enable the simulation of complex construction scenarios that would

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otherwise be difficult or unsafe to reproduce in real training environments. In addition, VR technologies are increasingly being explored as tools for enhancing behavioural safety training within the construction industry.

Despite the growing interest in VR applications for construction safety training, existing studies primarily focus on evaluating training effectiveness rather than providing systematic methodological guidance for developing immersive training environments [9]. Limited research has addressed how VR safety training systems should be structured to integrate behavioural safety principles, experiential learning processes, and risk perception mechanisms. This methodological gap is particularly evident in work at height contexts, where realistic hazard simulation and behavioural decision-making are critical components of effective safety training. This paper describes the structured methodology for developing immersive VR-based safety training environments, known as the VIRTRON. The proposed methodology integrates behavioural learning theories with immersive VR technology to guide the design of safety training simulations.

Accordingly, the objective of this paper is to present the overall methodology designed to develop VIRTRON, starting from the identification of critical work at height accident scenarios and behavior-related risk factors in construction activities, to the usability and perceived training effectiveness of the VIRTRON system through user acceptance testing (UAT). By documenting this structured development process, the study provides a replicable methodological reference for future VR-based safety training development in construction environments.

2 Literature Review

2.1 Limitations of Conventional Safety Training

Safety training is widely recognised as one of the most important preventive strategies for reducing accidents in the construction industry. Conventional training approaches primarily focus on communicating safety rules, procedures, and regulatory requirements to workers. Although such methods are useful for improving workers' declarative knowledge of safety regulations, they often provide limited opportunities for experiential learning and behavioural development [5]. A major limitation of conventional safety training is its passive instructional format. Lecture-based delivery methods are often considered not able to stimulate cognitive engagement or emotional involvement among workers, resulting in weaker knowledge retention and limited behavioural transfer to real construction environments [11]. Construction sites are complex environments where workers must continuously interpret evolving hazards and make rapid safety decisions. However, traditional training environments rarely replicate these situational complexities, which contributes to a persistent gap between safety knowledge acquisition and actual on-site behaviour [7, 8]. Furthermore, conventional safety training often emphasises compliance rather than behavioural change. Whilst compliance-based approaches may improve awareness of safety regulations, they seldom strengthen workers' ability to recognize hazards or assess risks effectively during real construction activities [6]. Empirical studies suggest that effective safety training should incorporate experiential exposure, allowing workers to interact with realistic hazard scenarios and understand the potential consequences of unsafe actions [12]. Furthermore, another limitation of conventional safety training is the lack of contextual realism. Work at height activities involve spatial awareness, perception of height-related risks, and the ability to make decisions under uncertainty. These cognitive and perceptual elements are difficult to replicate using traditional classroom-based approaches. As a result, workers may struggle to translate theoretical safety knowledge into practical behaviour in real site conditions.

2.2 Immersive Virtual Reality (VR) in Construction Safety Training

Immersive VR has emerged as a powerful technology for enhancing safety training effectiveness in construction environments. Immersive VR systems typically use head-mounted displays (HMDs), motion tracking sensors, and interactive three-dimensional environments to create realistic simulations that enable users to experience virtual scenarios as if they were physically present within them. This psychological experience, commonly referred to as "presence", plays a critical role in immersive learning environments [9]. High levels of presence in VR environments can considerably influence cognitive engagement, emotional response, and behavioural intention. Immersive simulations would allow users to actively interact with virtual hazards and perform tasks in complex scenarios, thereby giving the workers experiential learning processes. Within the safety context of the construction industry, immersive VR enables workers to experience hazardous situations associated with working at heights without exposing them to actual physical risks.

Previous studies have demonstrated the effectiveness of VR-based training in improving hazard recognition and situational awareness among construction workers. For example, Sacks found that workers who participated in immersive VR safety training performed significantly better in hazard identification tasks compared to those who received conventional training [13]. Similarly, Zhao and Lucas reported that VR simulations improved workers' ability to recognize hazardous conditions and respond to safety risks in construction environments [14]. Li and Wu have also indicated that immersive training environments can help to strengthen cognitive processing and emotional engagement, both of which are critical factors in promoting behavioural change in safety training [15, 16]. Therefore, within the context of work at height activities, immersive VR provides a particularly valuable training platform. VR simulations are seen as a technological tool to replicate spatial hazards, height perception, unstable platforms, and fall risks that are difficult to reproduce safely in real-world training environments. Hence, VR training is seen to help enhance risk perception and encourage safer behavioural responses [14].

Despite the increasing adoption of VR technologies in construction safety research, many existing applications remain primarily technology-driven rather than pedagogy-driven. That is, the development of VR training systems often focuses on technical implementation without adequately integrating learning theories or behavioural safety principles. Therefore, there is a need to develop a structured immersive VR safety training environment.

2.3 Theoretical Foundation

The development of the VIRTRON methodology is grounded in three complementary theoretical perspectives: experiential learning theory, risk perception theory, and immersive learning principles. Integrating these theories provides a pedagogical foundation for designing immersive VR training environments that promote behavioural safety outcomes. The theoretical foundations are explained as follows:

i. Experiential Learning Theory
Experiential Learning Theory (ELT), proposed by Kolb, emphasises that learning occurs through the transformation of experience [17]. According to Kolb's model, effective learning involves a cyclical process consisting of four stages: concrete experience, reflective observation, abstract conceptualisation, and active experimentation. Within a VR training environment, immersive simulations provide users with experiences of hazardous situations. Users can reflect on their actions, receive feedback, and apply improved safety strategies in subsequent scenarios. This experiential learning cycle supports deeper cognitive understanding and behavioural reinforcement.

ii. Risk Perception Theory
Risk Perception Theory highlights the importance of how individuals perceive and interpret risk when making safety-related decisions [18]. In construction environments, workers may become adapted to hazardous conditions and progressively underestimate potential risks. This phenomenon, often referred to as risk normalization, can reduce compliance with safety procedures and increase accident likelihood. Immersive VR simulations can influence risk perception by exposing users to realistic hazard scenarios.

iii. Immersive Learning Principles
Immersive learning principles are further explained through the Cognitive Affective Model of Immersive Learning (CAMIL), proposed by Makransky and Petersen [10]. CAMIL suggests that immersive technologies influence learning outcomes through psychological mechanisms such as presence, emotional engagement, and cognitive processing. According to this model, immersive environments enhance attention, motivation, and knowledge retention, which can ultimately improve behavioural performance. Within the VIRTRON training environment, the immersive learning principles guide the design of interactive hazard scenarios, feedback mechanisms, and behavioural learning cycles.

3 Research Methodology

Given the exploratory and framework-development nature of this study, a mixed-method research strategy will be adopted to support the development of the VIRTRON training environment. The development of the VR-based safety training involves integrating several components, as mentioned previously in section 2.3. Understanding how these elements interact requires interpretative exploration rather than relying solely on statistical measurement. To support the development of the VIRTRON training environment, several data collection techniques are proposed to be employed, such as document analysis, questionnaire survey, and focus group discussions (FGDs) with subject matter experts. A questionnaire survey has been conducted to identify common types of work at height accidents and contributing risk factors in construction activities, providing quantitative insights into prevalent safety issues. The findings from the survey will then be discussed in focus group sessions with safety professionals, academics, and VR development specialists. These discussions would then help to interpret the survey results and translate them into realistic immersive training scenarios for VIRTRON.

Participants for the FGD will be selected via purposive sampling to ensure they possess relevant expertise in construction safety, occupational health, or immersive technology development. The collected qualitative data will then be analysed using thematic analysis following the procedure proposed by Braun and Clarke (2021). This method allows the identification of recurring patterns, behavioural indicators, and design principles that inform the development of the immersive VR safety training framework. Although qualitative research provides rich contextual insights, its findings may have limited generalisability due to differences in regulatory environments, organisational practices, and technological readiness across construction sectors. Nevertheless, the purpose of this study is not statistical generalisation but rather the development of a structured and theory-driven VR training environment. The resulting VIRTRON is intended to serve as a foundational model that can be further evaluated through future experimental or quantitative studies.

4 Research Design

The development of VIRTRON has been divided into four main phases of the research process, which can be seen in Figure 1, comprising: Phase 1: Initiation, Phase 2: Methodology and Instrument Development, Phase 3: Embedded Case Study (Pre-Development and Development), and finally Phase 4: Validation. This structured design ensures a coherent progression from theoretical exploration to practical implementation within the VIRTRON immersive training system.

4.1 Phase 1: Initiation

The initiation phase establishes the conceptual and theoretical foundation of the research through a structured literature review. This phase critically synthesises extant literature on construction safety training, types of work at height accidents, factors associated with work at height accidents, behavioural safety performance, foundation theories associated with the development of the VR training environment, and immersive virtual reality applications in training environments, as well as the technological requirements.

Relevant academic databases such as Scopus and Web of Science are systematically searched using keywords including construction safety training, work at height hazards, VR safety training, VR technological development, hazard recognition, and risk perception. The review prioritises peer-reviewed journal articles published within the last decade, particularly those appearing in high-impact journals. The purpose of this phase is to identify existing research gaps, theoretical limitations, and methodological challenges in current safety training approaches, as well as being the foundation of the development of the VIRTRON.

4.2 Phase 2: Research Instrument and Methodology Development

The second phase focuses on defining the research objectives and developing appropriate data collection instruments (See Figure 1). Based on the literature review and theoretical framework, several research instruments will be developed to support data collection.

These instruments include the survey questionnaire for the identification of common work at height accident scenarios and contributing risk factors, a focus group discussion (FGD) protocol to be used to gather expert insights regarding realistic training scenarios and immersive system design, and finally the measurement scales for evaluating usability, perceived usefulness, and behavioural relevance of the VR training system. Before the data collection, a pilot study will be conducted with a small group of experts to assess the clarity, relevance, and validity of the research instruments. Feedback from the pilot test will be used to refine the questionnaire and interview protocols to improve content validity and reliability.

4.3 Phase 3: Embedded Case Study

Phase three represents the core development stage of the research, where theoretical insights and empirical findings will be translated into a structured immersive VR safety training framework (See Figure 1 for details). This phase adopts an embedded case study approach, allowing multiple sources of evidence to be integrated during the system development process.

The phase consists of two stages, which are the pre-development, which comprises the design of the immersive VR training environment, and next is the development of the environment itself.

4.3.1 Stage I: Pre-Development

The pre-development stage establishes the empirical and regulatory foundation for designing immersive VR training scenarios. Findings from the secondary data sources, such as national safety guidelines, construction safety regulations, accident reports, and standard operating procedures, are to be used as a framework for the development of VIRTRON. This framework will be triangulated with findings from the FGD conducted with construction safety officers, academics, and industry practitioners. The integration of document analysis and expert insights ensures that the immersive VR scenarios reflect real industry conditions and regulatory requirements. The results of this stage firm the hazards often faced during work-at-heights and confirm the recognition, situational awareness, risk perception, and behavioural intention of workers with the associated hazards. The outcome from the FGD would be a complete design to be used for the development of VIRTRON.

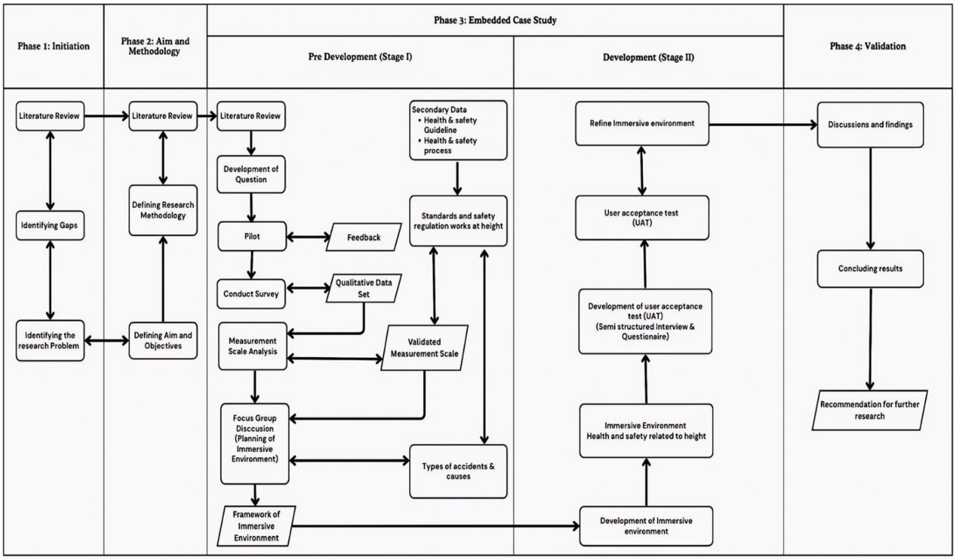
4.3.2 Stage II: VR System Development

During the development stage, the validated framework and behavioural constructs will be translated into VIRTRON. Realistic three-dimensional construction environments are created to simulate work at height scenarios, including scaffolding work, roof-edge operations, ladder usage, and elevated platform tasks. The interactive simulation elements include hazard identification tasks, scenario-based decision-making pathways, behaviour-triggered consequences, and immediate corrective feedback.

4.3.3 Phase 4: Validation

The final phase evaluates the usability and perceived effectiveness of the VIRTRON training system through User Acceptance Testing (UAT). This evaluation will assess how users interact with the system and whether the immersive training environment supports safety learning objectives. The data collection technique used for this phase would be a questionnaire. The questionnaire instrument will be developed based on constructs derived from the Technology Acceptance Model (TAM), including perceived usefulness and perceived ease of use [19, 20]. Additional evaluation dimensions include training realism, user engagement, and behavioural relevance. The collected data will then be analysed to identify system strengths, usability limitations, and opportunities for further improvement. Feedback obtained from users will then be used to refine the immersive training environment and optimise system functionality. This validation process enhances the practical applicability and credibility of the VIRTRON framework while providing empirical insights into the use of immersive VR technologies for construction safety training. Figure 1 shows the overall research process proposed for the development of VIRTRON.

Figure 1: Proposed Research Process for VIRTRON



5 Conclusion

Work at height activities remain as one of the major sources of accidents and fatalities in the construction industry. The conventional safety training methods often rely on compliance-based instruction and may provide limited opportunities for workers to experience realistic hazardous situations. This study proposes the VIRTRON framework, a structured methodology for developing immersive VR safety training environments for work at height construction activities.

The proposed methodology integrates experiential learning theory, risk perception theory, and immersive learning principles to guide the design of a behaviour-oriented VR safety training environment. By combining these theoretical perspectives with immersive technology design, the framework outlines a systematic process for developing realistic training scenarios that allow workers to interact with simulated hazards in a controlled environment.

This proposed methodology contributes to construction safety research by providing a structured reference for developing theory-informed VR training systems. In addition to its theoretical contribution, the framework may also offer practical guidance for safety practitioners and training developers interested in adopting immersive technologies for safety education in construction environments. Future research will focus on the development and evaluation of the proposed VR training environment. Experimental studies may be conducted to examine the effectiveness of immersive VR training in improving hazard recognition and safety behaviour among construction workers.

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