# Mississippi DOT Virtual Reality Safety Training Study

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**16. Abstract**
This project report presents the development and assessment of a VR-based safety training system to improve training effectiveness and situational awareness for construction workers in work zones. An essential feature of the developed VR-based safety training system is the enhanced Human-Technology Interactions (HTIs) with near real-time feedback during training to enhance learning effectiveness and experience. The developed system consisted of a computer, a VR headset, two controllers, and three body trackers. Two safety issues, (i) struck-by hazards and (ii) ergonomic risks, were included in the training system. The training system was assessed using system performance metrics, including knowledge gain and motivation, as well as system design metrics that included simulation sickness, system usability, and user experience. Experiments were conducted with ten undergraduate students in Civil Engineering from Mississippi State University to test and evaluate the developed VR system. The obtained results demonstrated above-average performance for all performance and design metrics (i.e., knowledge gain, motivation, simulation sickness, system usability, and user experience). The project findings indicated that the enhanced HTIs and near real-time feedback mechanism in the developed VR-based safety training system improved users' knowledge gain and safety awareness. The outcomes of this project could provide insights for MDOT to enhance its current safety training practices, e.g., adopting VR-based systems with enhanced HTIs for safety training and customizing training modules based on MDOT's safety needs.

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## Author Acknowledgments

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# Table of Contents

# List of Tables

# List of Figures

# List of Abbreviations

| | |
|---|---|
| DOT | Department of Transportation |
| HTIs | Human-Technology Interactions |
| IRB | Institutional Review Board |
| MDOT | Mississippi Department of Transportation |
| MSLQ | Motivated Strategies for Learning Questionnaire |
| MSU | Mississippi State University |
| PPE | Personal Protective Equipment |
| PQ | Presence Questionnaire |
| SD | Standard Deviation |
| SSQ | Simulation Sickness Questionnaire |
| SUS | System Usability Scale |
| VR | Virtual Reality |
| WMSDs | Work-Related Musculoskeletal Disorders |

# Executive Summary

Work zones pose significant safety risks to construction workers who are building, repairing, and maintaining roads, bridges, and utilities, emphasizing the need for effective safety training methods. Virtual Reality (VR) has become a viable alternative to enhance the safety training of construction workers. However, the current VR-based safety training methods lack real-time feedback during the training, which limits the effectiveness of the training.

This project conducted the development of safety training that integrated VR and body trackers and implemented enhanced Human-Technology Interactions (HTIs) to improve learning effectiveness and safety awareness. Two safety hazards in work zone environments were selected for training in this project: struck-by hazard and ergonomic hazard. In the developed VR-based training system, the VR environment immersed trainers in a realistic work zone while body trackers captured the trainees' postures and movements. A near real-time feedback mechanism was developed and implemented to provide immediate feedback about the trainee's actions to improve the learning effectiveness and experience during the training. In summary, the enhanced HTIs achieved in the developed VR system enabled users' behaviors and operations to be monitored, and accordingly, users were able to adjust their behaviors and operations during the training based on the timely feedback provided by the VR system.

The developed system was evaluated by conducting experiments with ten undergraduate students in Civil Engineering at Mississippi State University (MSU). Approval for the experiments was obtained from the MSU Institutional Review Board (IRB) (IRB# 22-083). The metrics used to evaluate the effectiveness of the training system included knowledge gain, motivation, simulation sickness, system usability, and user experience. The developed training system demonstrated above-average performance for all adopted metrics. The system achieved minimal symptoms of simulation sickness and positive responses from participants regarding system usability.

In summary, this project introduced real-time feedback in VR-based safety training to emphasize the importance of effective learning and engagement. Furthermore, the obtained outcomes indicated the improved knowledge gain and overall effectiveness of safety training in work zones. In the future, conducting more experiments with construction workers will provide more insights into the developed training system. Conducting a comparative analysis with the traditional training methods and systems and incorporating more hazard types are expected to help develop more comprehensive VR-based safety training approaches. The outcomes of this project could provide insights for MDOT to enhance its current safety training practices, e.g., adopting VR-based systems with enhanced HTIs for safety training and customizing training modules based on MDOT's safety needs.

# Chapter 1. Introduction

## 1.1. Background and scope of this project

Construction work zones can be risky environments that require additional careful attention during safety management. Work zones pose hazards to machine operators, drivers, and workers when constructing, repairing, and maintaining roads and bridges. From 2011 to 2020, fatal crashes in work zones increased from 367 to 432 cases in the US, and fatalities rose from 401 to 479, indicating an increase of around 19.5% (CPWR, 2022). The fatalities among construction, maintenance, utility, and transportation workers accounted for 21% to 32% of work zone fatalities (National Work Zone Safety, 2024). Additionally, non-fatal injuries such as musculoskeletal disorders (MSDs) are prevalent in highway, street, and bridge construction. Specifically, an average of 920 cases in the above-mentioned construction were reported annually from 2011 to 2020. These injuries typically resulted in an average of 17 days off work per incident (CPWR, 2023). Implementing effective safety training programs is a critical strategy to enhance workers' safety in work zones.

Virtual Reality (VR)-based safety training has been getting researchers' attention for several reasons, such as immersive and engaging experience, exposure to hazardous scenarios without real risk, repeatability and consistency, customization and scalability, and data collection and performance tracking (Chen & Chein, 2022; Hamilton et al., 2021; Manning et al., 2020). For example, Bin et al. (2019) developed a VR-based safety training, focusing on scenarios related to construction, such as bridge, road, and tunnel construction. Roofigari-Esfahan et al. (2022) developed a VR platform that allows instructors to create, adapt, and share work zone scenarios with a group of highway workers to improve hazard recognition, evaluation, and control for highway construction workers. Furthermore, a timely feedback system in VR-based safety training is essential for trainees to perform the correct safety procedures, reinforce those behaviors, and increase the likelihood of remembering and applying them in real-world situations (Aati et al., 2020; Jacobsen et al., 2022). However, studies focusing on a timely feedback system for the trainees in a VR environment to enhance training effectiveness are very limited, particularly for construction workers in work zones.

This project aims to develop a VR-based safety training system with enhanced Human-Technology Interactions (HTIs) for construction workers in work zones, which provides near real-time feedback to trainees to enhance training effectiveness and situational awareness. Based on the existing literature and related injury statistics, two safety issues, (i) struck-by hazards and (ii) ergonomic risks, specifically work-related musculoskeletal disorders (WMSDs), are considered in this project to explore the developed safety training system for workers in work zones. The developed system was evaluated based on system performance metrics, including knowledge gain and motivation, and system design metrics, including simulation sickness, system usability, and user experience. The safety training system developed in this project can also be extended to address other safety issues. This project demonstrates how timely feedback and enhanced HTIs improve the effectiveness of VR-based safety training and increase knowledge gain using immersive technologies to improve workers' safety awareness in work zones.

## 1.2. Objectives

Despite the development of different safety training methods using VR, there is a lack of studies focusing on VR-based safety training with enhanced HTIs for construction workers in work zones. Further investigation is needed for VR-based training methods that offer immediate feedback and improved interactions to enhance knowledge gain and safety awareness. Therefore, the objectives of this project are:

- Identify and design the training scenarios in VR environment for the safety issues considered;
- Develop a VR-based safety training system enabling and enhancing the interactions between users and the adopted technologies to enhance the effectiveness of the training;
- Examine and evaluate the performance and effectiveness of the developed VR-based training system.

## 1.3. Organization of the report

This report consists of six chapters. Chapter One provides background information on VR-based training and outlines the report’s objectives. Chapter Two reviews the literature on VR-based safety training in construction, HTIs, and evaluation metrics for VR system assessments. Chapter Three presents an innovative VR-based safety training framework, including VR-based system development and assessment. Chapter Four discusses the details of the experiment design, data collection, results of the system performance and system design assessment, and a discussion of the findings. Chapter Five presents the conclusions of the project, discusses recommendations and practical implications, and outlines limitations and future directions.

# Chapter 2. Literature Review

## 2.1. VR-based safety training in construction

VR technology has garnered attention in construction safety training for various reasons including simulating realistic scenarios, providing engaging learning experiences, reducing safety risks during training, and cost-effectiveness (Chellappa et al., 2022; Harichandran et al., 2022; Wu et al., 2020; Xu et al., 2020). Jeelani et al. (2019) developed stereo-panoramic environments from real and virtual construction sites to deliver instructional elements. The study achieved a 39% improvement in hazard recognition and a 44% improvement in hazard management performance after training. Xu et al. (2024) demonstrated the effectiveness of VR-based safety training through embodied cognition and emotional arousal. This study was based on controlled experiments that compared paper-based training, VR-based learning, and VR-based experiences among novice learners and those with prior knowledge. Li et al. (2022) implemented individual training preferences and target training time by assessing users' hazard identification skills, particularly the four common hazards, i.e., struck-by hazards, fall hazards, caught-in/between hazards, and electrical hazards before the VR-based training. Yu et al. (2022) conducted experiments to quantify the effectiveness of immersive VR-based safety training for novice (college students) and experienced specialties (construction practitioners). The improvement in safety learning performance of novice workers was higher than that of experienced workers, 5.4% higher in Personal Protective Equipment (PPE) and 15.9% in hazard scenario identification (HSI). Seo et al. (2024) proposed an interactive immersive VR-based training framework that includes four interactive learning elements: immediate feedback, basic interaction with objects, assembling objects, and knowledge testing. This study identified immediate feedback and basic interaction with objects as key factors in improving personal learning outcomes during training.

Work zone hazards for construction workers occurred due to working close to construction equipment and high-speed traffic. Chang et al. (2020) proposed VR-based training for the State Department of Transportation (DOT) inspection staff on traffic control protocols and standards. The training module consisted of roadway geometrics, work zone signage, traffic control devices in a VR environment, and motion capture to capture the actual movement of the flagger working in the working zone. Ergan et al. (2020) conducted a study that analyzed worker behavior by integrating wearable sensors and VR to determine when, how, and at what frequency to push alarms in a dangerous situation. The authors considered three scenarios based on real incidents: setting up barriers to define the work zone, marking the road on the highway, and installation of traffic sensors. Qing and Edara (2024) developed a VR-based training module that enables two trainees to take a work zone flagger training course at a time. The module consists of interactive activities such as using stop/slow paddles, teleporting to various locations, and picking up and relocating traffic cones to control traffic. However, safety training studies that focus on work zones using VR are limited and require further investigation to enhance worker safety.

## 2.2. HTIs in VR-based safety training

HTIs in VR-based safety training pertain to how users engage with the virtual environment and its components. HTIs encompass user interface design, sensory inputs, and feedback mechanisms, influencing trainees' ability to engage and transfer the required knowledge from the simulations. HTIs involve interactions with virtual objects, machinery, and other users within the VR setting (Robert, 2023). Slater et al. (2022) explained that the sense of “being there” in the virtual environment is composed of Place Illusion (being in the place in the VR) and Plausibility (events happening in virtual situations). Their study demonstrated that the two elements showed how users perceived and interacted with the virtual environment, indicating the technology's effectiveness in simulating reality (Slater et al., 2022). User experience is another essential element in the human-technology interaction of a VR-based system, which affects the training system’s effectiveness. Weech et al. (2019) found that individual differences in spatial awareness and experience with VR affected the susceptibility to cyber sickness. Furthermore, a sense of presence in VR and the experience of cybersickness showed negative relationships (Weech et al., 2019). The other factor in HTIs in VR training is the cognitive load required to interact and understand the virtual environment. Mikropoulos and Natsis (2011) discussed managing cognitive load in VR environments, i.e., avoiding overly complex VR environments, designing interfaces that will not distract users, and creating an appropriate level of presence to improve the learning outcome. Thomay et al. (2023) developed cognitive load-based decision-making in VR training to achieve dynamic training scenarios in the medical field. In this study, to adjust the cognitive load, training parameters were prepared to maintain an optimum learning level, and cognitive level control was achieved through implementing algorithms using eye tracking and pupillometry.

Studies that focus on HTIs in VR-based safety training in construction safety training are very limited; recent studies are as follows. Akanamu et al. (2020) presented a postural training system for wood frame construction. The system provided real-time feedback through a user interface to demonstrate its effectiveness in ensuring workers' safety. Dias Barkokebas et al. (2023) integrated VR and inertia capture systems to assess postures through real-time body motion acquisition and processing. This system demonstrated the effectiveness of auditory and visual feedback interventions. Xu and Zeng (2021) developed an immersive and interactive multiplayer-based training platform that integrates a VR platform by enabling repeatable and flexible procedures to improve safety awareness. Studies have shown that providing immediate feedback through data collection and automated analysis in VR settings improves trainees' ability to adjust based on the feedback. This approach resulted in more engaging training sessions, increased knowledge acquisition, and improved retention (Abbas et al., 2023; Jacobsen et al., 2021). Few studies have explored integrating near real-time feedback with enhanced HTIs in VR-based training to improve knowledge gain and training effectiveness for construction workers in work zones.

# Chapter 3. Methodology

## 3.1. Framework of the VR-based work zone safety training system

The framework of the VR-based work zone safety training system is shown in Figure 1. An essential feature of the developed VR-based safety training system in this project was the enhanced HTIs with near real-time feedback during training to enhance learning effectiveness and experience (e.g., users' behaviors and operations were monitored by the training system, and accordingly, users were able to adjust their behaviors and operations during the training based on the timely feedback provided by the system). This system aimed to provide training on the proper use of PPE, safe working practices within work zones, and techniques for lifting heavy objects from waist and floor levels. The VR-based work zone safety training was divided into three modules: (i) an introduction module that provided a tutorial with instructions and practices on how to use the VR devices, background information (such as the training needs), and an overview of the subsequent modules, (ii) a struck-by hazard training module, and (iii) an ergonomics training module (Gugssa et al., 2024). By providing a highly interactive and engaging training experience, the system aimed to enhance users' ability to recognize and respond to potential hazards, ensuring greater safety and efficiency at work zone job sites.

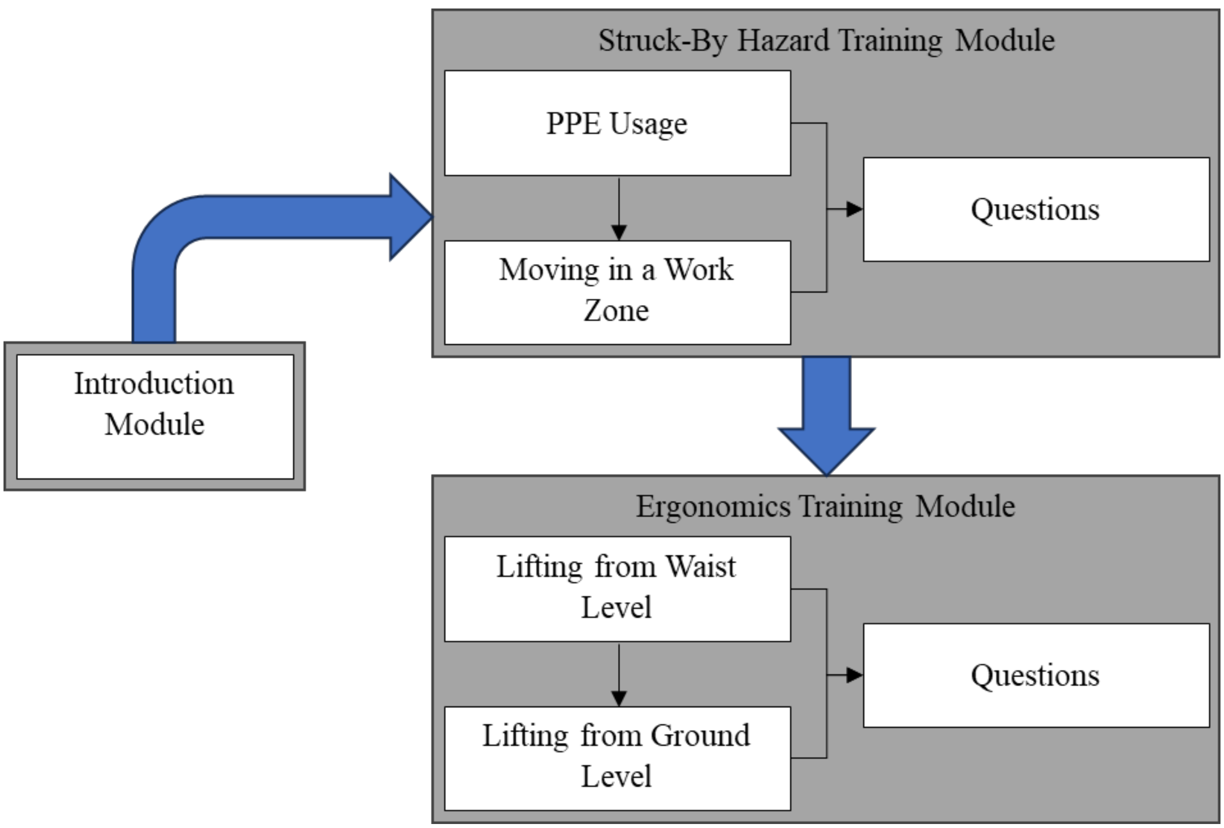



**Figure 1. Framework of VR-based work zone safety training system**

### 3.2. VR system development

The development of the VR-based safety training system was carried out to meet the project's objectives effectively. The developed training system included the following components: a VR headset, three body trackers (two for the feet and one for the waist), two tracking stations, two hand controllers, and a computer (Gugssa et al., 2024). Unity 2021 software was used to create a 3D virtual environment. VIVE trackers were employed to track body movements, and Manus Polygon Core 1.9 software was utilized to analyze body joints, as shown in Figure 2.


**Figure 2. Computer, VR headset, controllers, and body trackers for the training system**

The first module in the VR system was the introduction module (Figure 3) which provided a tutorial with instructions and practices on how to use the VR devices (such as controllers), background information (such as the training needs), and an overview of the subsequent modules. At the beginning of the struck-by hazard training module, a roadmap was provided, listing the main parts included in the current module (Figure 4). The struck-by hazard training module consisted of three parts. The first part provided training and practices about the uses of PPE in work zones, including the correct usage of safety vest types based on vehicle speed and work zone settings (The training also covered the limitations of Class 1 vests, emphasizing that they are not suitable for use in work zones. Understanding what should be avoided in work zones also is essential for enhancing workers' safety awareness and ensuring compliance with safety standards). Figure 5 shows examples of the training on PPE usage, and Figure 6 shows an example used for practices about the selection of PPE based on the provided work zone settings. The second part of the struck-by hazard training module provided training and practices for working safely in work zones with moving equipment. The task used as an example was to place a safety cone at a designated place in the road after crossing an area in the work zone with two pieces of moving equipment (a dump truck and a roller). To complete this task safely, the user must check the surroundings frequently, maintain sufficient eye contact with the equipment operators, and keep a safe distance from each equipment (Figure 7). During the practices in this module (Figure 8), the users received timely feedback on their operations, e.g., whether the appropriate PPE was selected for the given work zone environment and settings, whether the user completed the corresponding step before taking the following action in the dynamic work zone to place the safety cone, whether the user maintained sufficient eye contact with the equipment operators and others. The third part of this module was to answer related questions at the end of each training scenario to test and improve the knowledge gained, as shown in Figure 9. Users can only proceed after they have answered all the questions correctly.


(a)

(b)

**Figure 3. Introduction module of the VR-based training: (a) training on how to use VR controllers and (b) safety background information**

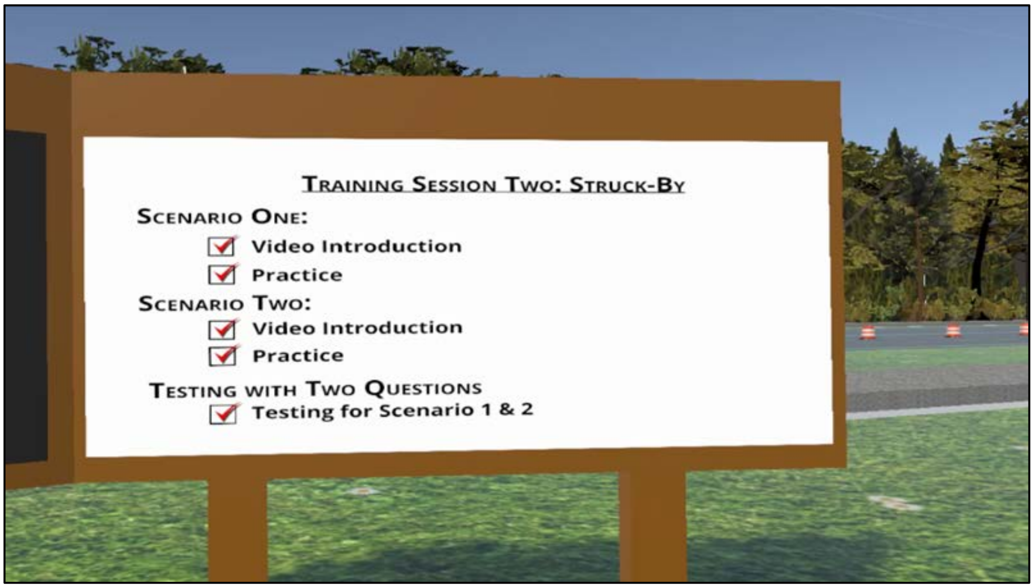
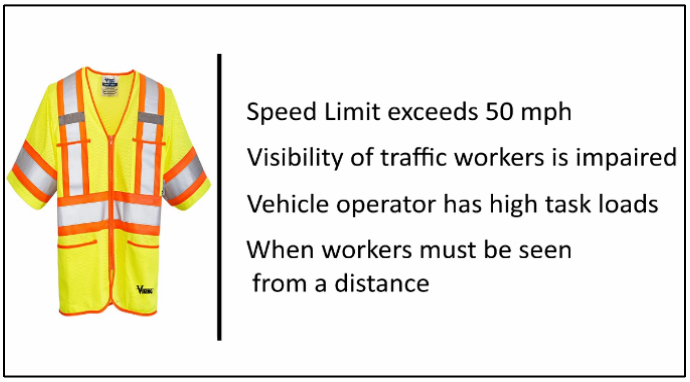



**Figure 4. Struck-by hazard training module: a road map of the current training session**


(a)




(b)

**Figure 5. Scenario one in the struck-by hazard training module: (a) and (b) sample PPE**


**Figure 6. Scenario one in the struck-by hazard training module: practices on the selection of PPE based on the provided work zone settings**

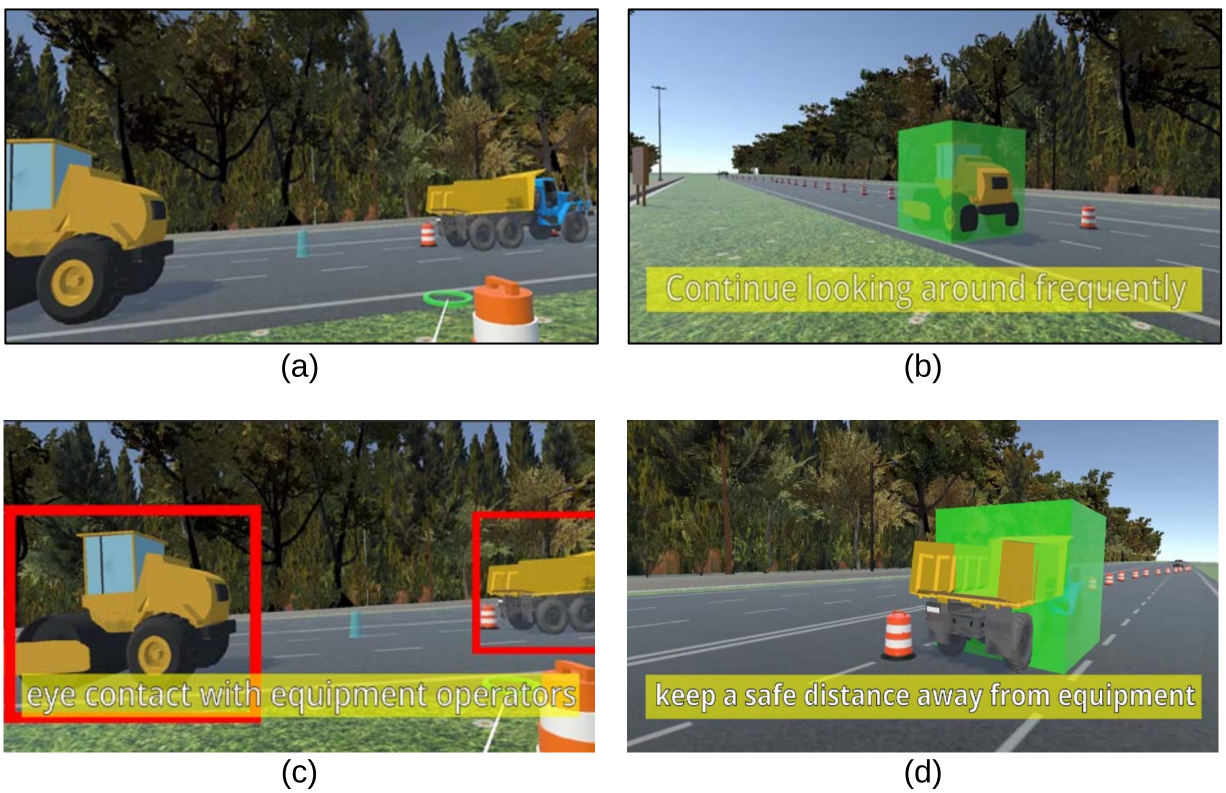
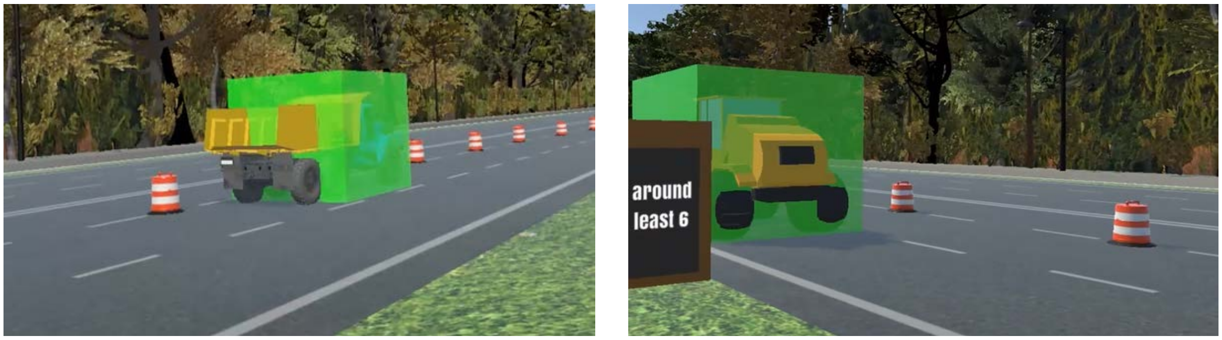



**Figure 7. Scenario two in the struck-by hazard training module: (a)-(d) training and instructions on working safely in work zones with moving equipment**




(a) (b)

**Figure 8. Scenario two in the struck-by hazard training module: (a) and (b) practices on working safely with moving equipment in a work zone**


**Figure 9. Questions in struck-by hazard training module to test and improve users' knowledge**

At the beginning of the ergonomics training module, a roadmap was provided, listing the main content included in the current module (Figure 10). The ergonomics training module included two major tasks to explore and investigate the system, i.e., heavy lifting from the waist and ground level, respectively. A demonstration of each of the two lifting tasks was provided first before the users conducted the lifting in the virtual environment (sample screenshots are shown in Figures 11 and 12). Both types of lifting were divided into several essential steps, and each step was shown on the virtual environment screen with instructions and demonstrations. In the practice section, users performed each posture at the same time following the illustration and feedback received on the screen and could only proceed once the current posture was considered correct and safe. Based on the illustrations and feedback received, the users could adjust their postures until the system detected them as sufficiently safe. Figures 13 and 14 show the practice section and near real-time feedback mechanism for lifting from the waist level and ground level, respectively. In the end, some related questions were provided to further test and improve the knowledge gained in the VR environment, as shown in Figure 15.

For both training modules (struck-by and ergonomic), users' body movements (including head) were collected and analyzed in near real-time by the system, and the outputs were displayed on the screen for users to check their activities, make adjustments, and take measures to improve the training effectiveness.

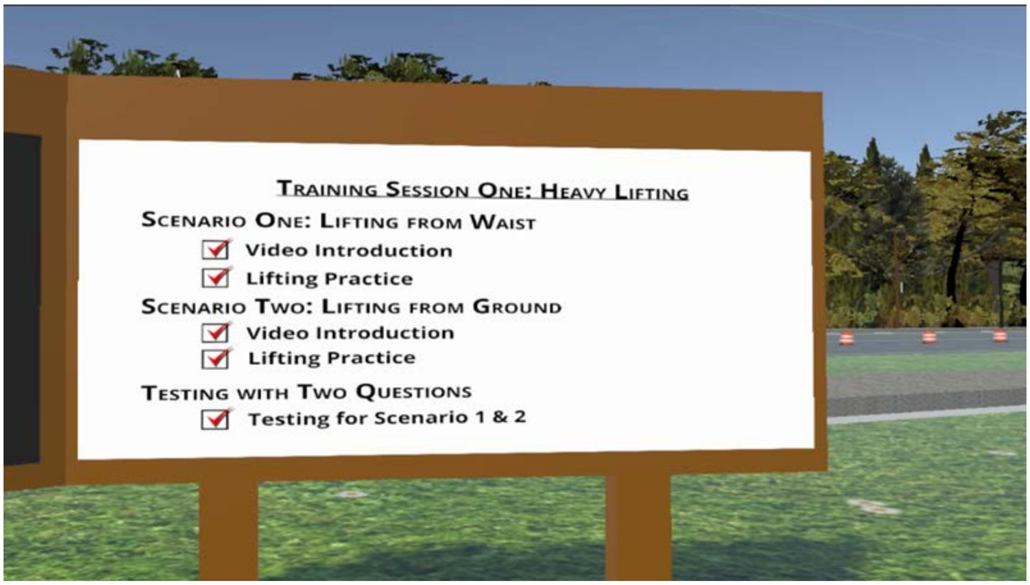
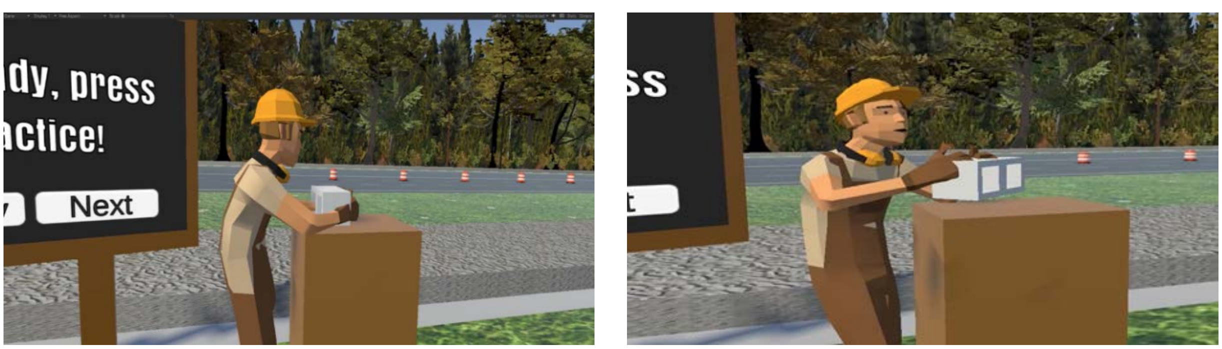


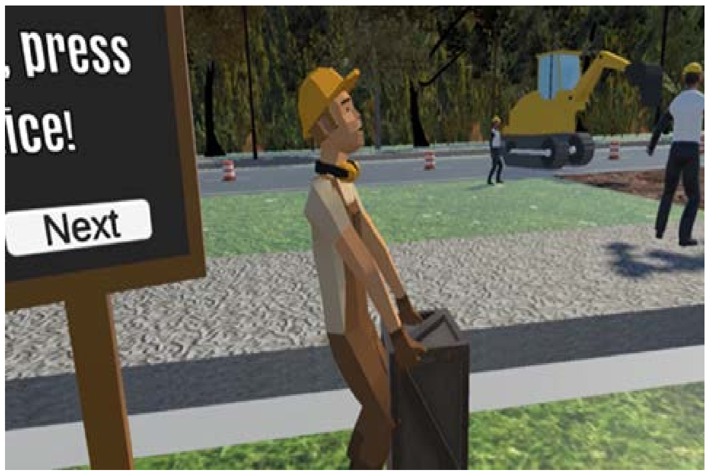

**Figure 10. Ergonomics training module: a road map of the current training session**




(a) (b)

**Figure 11. Scenario one in the ergonomics training module: (a) and (b) demonstration of lifting from waist level**

(a)




(b)

(c)

**Figure 12. Scenario two in the ergonomics training module: (a)-(c) demonstration of lifting from ground level**


**Figure 13. Ergonomics training module: (a)-(e) lifting practice from waist level and immediate feedback mechanism**

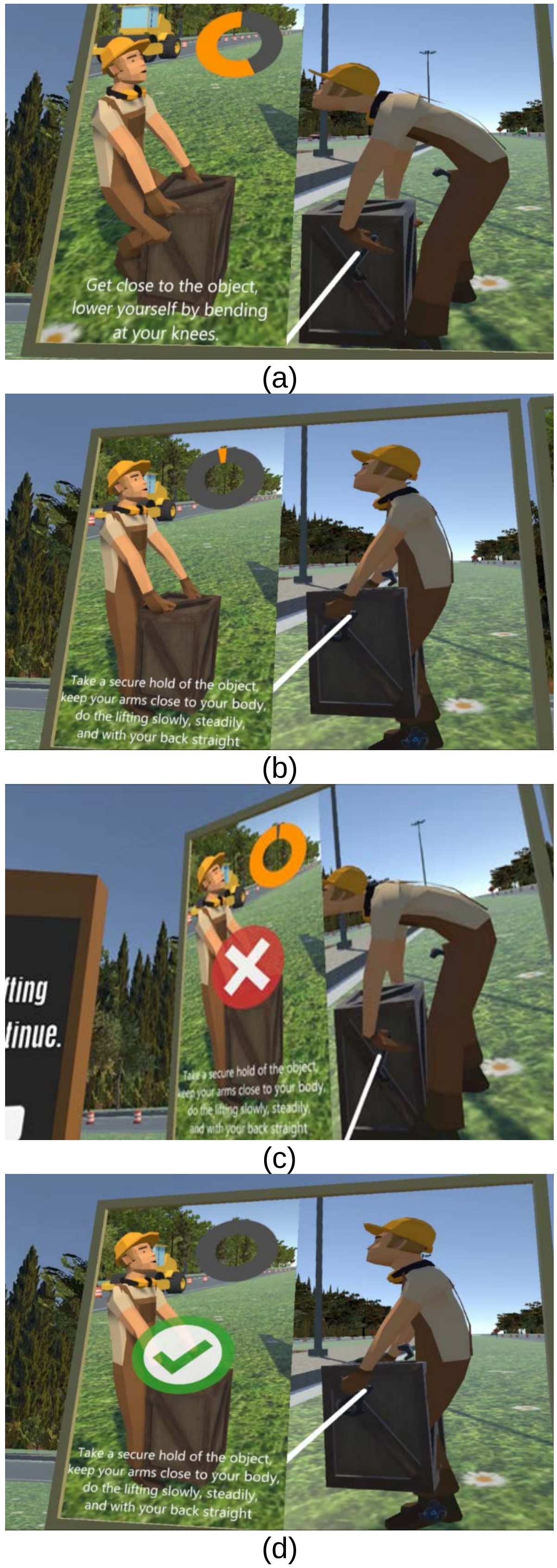



**Figure 14. Ergonomics training module: (a)-(d) lifting practice from ground level and immediate feedback mechanism**

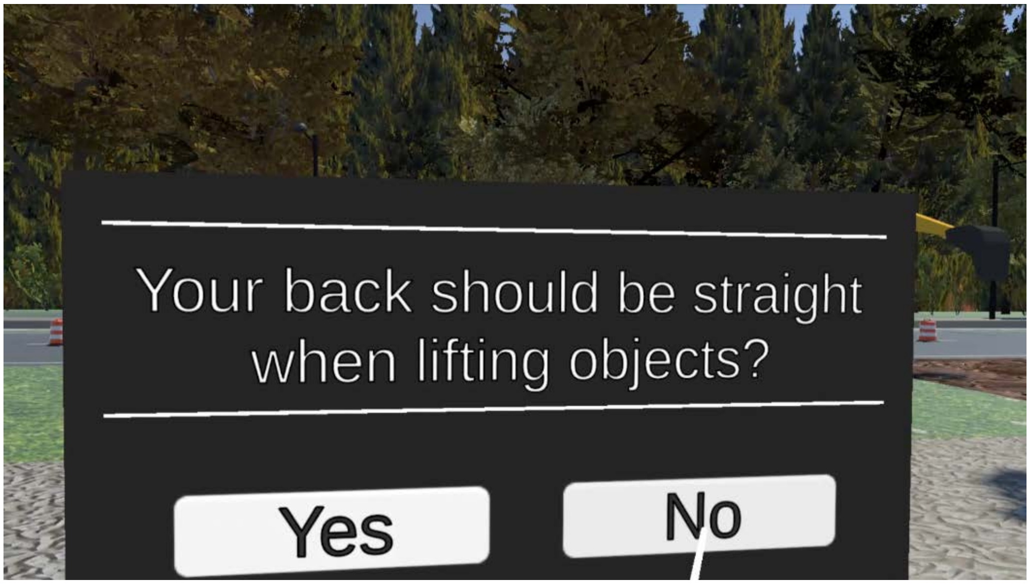



**Figure 15. Questions in the ergonomics training module to test and improve users' knowledge**

## 3.3. VR system assessment

The VR system assessment in this project mainly included two parts: system performance assessment and system design assessment. The system performance assessment involved analysis of knowledge gain and motivation of users. The system design assessment included simulation sickness, system usability, and user experience (Gugssa et al., 2024). The details of the adopted five assessment metrics are discussed in the following sub-sections.

### 3.3.1. Knowledge gain

Knowledge gain analysis focuses on measuring the increase in knowledge and understanding trainees' performance through using a VR system. This metric is crucial for assessing the effectiveness of the training content and the VR environment in facilitating learning (Chen, 2006). Joshi et al. (2021) conducted a knowledge gain analysis before and after VR and video training for safety in the precast concrete industry. This study demonstrated that the knowledge gained through the VR training method was higher than that achieved with the traditional (video) training method. Similarly, Ma et al. (2024) used a knowledge gain analysis to evaluate the educational performance of VR-based nursing education approaches by comparing knowledge levels before and after the training. However, the researchers recommended further investigation using a larger sample size to validate their findings. Furthermore, a study on the effects of VR in training simulators explored perception and knowledge gain, highlighting the potential of VR technology to enhance learning outcomes in military contexts (Menin et al., 2021). In conclusion, knowledge gain analysis in VR training studies has shown promising results, indicating that VR can be an effective tool for enhancing learning outcomes in safety training.

In this project, specific questions and practical exercises were developed to assess the level of knowledge gained from the safety training. For the struck-by hazard part, four questions about using PPE in work zones and safe practices for working around moving equipment were prepared and used. For the ergonomics part, two real-world lifting practices: lifting from the waist level and lifting from the floor level were implemented. The lifting processes of users were captured by a camera and accordingly, the lifting techniques were assessed. For both struck-by and ergonomics parts, the scores from pre-training tests and post-training tests were compared and analyzed to gain insight into the knowledge gain metric.

### 3.3.2. Motivation

Motivation evaluates the level of engagement and enthusiasm that trainees exhibit while interacting with a VR system. Higher motivation levels often indicate more engaging and effective training experiences (Chen, 2006). Chan et al. (2023) studied person-centered variables such as motivation and engagement in chemical laboratory safety training using a VR game. The research revealed that older employees over 50 may experience reduced motivation compared to younger employees under 30 due to the complexity of usability and their unfamiliarity with VR. Josh et al. (2021) demonstrated that motivation was not affected by gender in video safety training in the precast concrete industry. In contrast, male and female trainees gained different motivation levels in VR-based safety training cases. In conclusion, VR-based safety training could offer significant potential for enhancing motivation and engagement among trainees. However, factors such as age, gender, and technological familiarity play important roles in determining the effectiveness of these training programs. The immersive environments, interactive elements, and practical skill development opportunities in VR provide a more engaging and effective training experience.

A questionnaire was prepared based on the Motivated Strategies for Learning Questionnaire (MSLQ) and used in this project to assess users' motivational beliefs and self-regulated learning for the motivation analysis (Pintrich & de Groot, 1990). The questionnaire used in this project had eleven questions taken from the motivational beliefs questionnaire (Pintrich & de Groot, 1990; Ma et al., 2024). Each response scale ranged from 0 (Strongly Disagree) to 6 (Strongly Agree). Motivation results above average can be taken as acceptable.

### 3.3.3. Simulation sickness

Simulation sickness, also known as VR motion sickness, is a critical metric that assesses the physical comfort of users. It measures symptoms such as nausea, dizziness, and headaches that can occur during or after VR sessions. To quantify and assess simulation sickness, Kennedy et al. (1993) developed the Simulation Sickness Questionnaire (SSQ). This standardized tool categorizes symptoms into three distinct subgroups: oculomotor discomfort, disorientation, and nausea. The SSQ has become a widely adopted instrument for measuring and comparing the intensity of VR-induced discomfort across different systems and applications (Josh et al.,2021; Ma et al., 2024). Mitigating simulation sickness is paramount for enhancing user comfort and promoting sustained engagement and usability with VR technologies.

SSQ was used to assess the user's level of simulation sickness for the developed safety training system in this project. The SSQ questionnaire consisted of sixteen questions with three categories, including nausea (general discomfort, increased salivation, sweating, nausea, difficulty concentrating, stomach awareness, and burping), oculomotor (general discomfort, fatigue, headache, eye strain, difficulty focusing, difficulty concentrating, and blurred vision), and disorientation (difficulty, nausea, fullness of head, blurred vision, dizzy (eyes open and closed) and vertigo) (Kennedy et al., 1993; Brunnströma et al. 2018; Joshi et al., 2021). Each response scale ranged from 0 (lowest level) to 3 (highest level). The total SSQ score was calculated based on Equations (1)-(4), and the SSQ score is categorized as shown in Table 1 for result analysis and comparison.

$$N = \frac{[1] \times 9.54}{n} \quad (1)$$

$$O = \frac{[2] \times 7.58}{n} \quad (2)$$

$$D = \frac{[3] \times 13.92}{n} \quad (3)$$

$$TS = (N + O + D) \times 3.74 \quad (4)$$

Where [1] = Total sum for the nausea category,

[2] = Total sum for the odometer category,

[3] = Total sum for the disorientation category,

n = Total number of users,

N, O, and D = average value of nausea, oculomotor, and disorientation, respectively,

TS = Total simulation sickness score.

**Table 1. SSQ score overview (Source: Kennedy et al., 1993)**

| SSQ score | Overview |
|---|---|
| 0 | No symptoms |
| < 5 | Negligible symptoms |
| 5 - 10 | Minimal symptoms |
| 10 - 15 | Significant symptoms |
| 15 - 20 | Symptoms are a concern |
| > 20 | A problem simulator |

### 3.3.4. System usability

System usability evaluates how user-friendly and accessible a VR system is. This metric considers factors such as ease of navigation, intuitiveness of controls, and the overall user interface design (Ramaseri et al., 2021). High usability is vital for ensuring that trainees can effectively interact with the VR environment without unnecessary frustration. The System Usability Scale (SUS) has emerged as a widely adopted tool for evaluating perceived usability in VR systems (Brooke, 1996). In a study on a virtual training environment for gas operatives, researchers used SUS alongside sense of presence questionnaires to assess the effectiveness of the VR training system. The results indicated that most participants, regardless of gender, age, or VR experience, were comfortable in the VR training environment (Asghar et al., 2021). A recent study has also explored the psychological processes involved in VR safety training effectiveness. The study analyzing data from 248 construction workers who completed VR safety training found that telepresence experienced through VR and trainees' risk perception regarding occupational accidents significantly affected their satisfaction with the training, which in turn influenced its effectiveness (Yoo et al., 2023). In conclusion, system usability plays a crucial role in the success of VR-based construction safety training. While VR systems generally demonstrate satisfactory usability, factors such as user age, experience, and the design of interactions within the virtual environment can significantly impact the overall effectiveness of the training.

In this project, system usability was used to evaluate user expectations for the developed VR-based safety training system. Studies have assessed the usability of VR-based training systems using the standardized tool - SUS. In this project, ten questions were included from a study conducted by Brooke (1996). Each response scale ranged from 1 (lowest) to 5 (highest). The questionnaire comprised positively worded questions (1, 2, 3, 4, 5, 7, and 9) and negatively worded questions (6, 8, and 10). The scores were calculated for the positively worded questions by subtracting 1 from the responses. For each negatively worded question, the score was subtracted from 5. The total SUS score was calculated by summing the score from 1-10 and multiplying by 2.5. According to Josh et al. (2021), a total score of above 68 is considered that users are experiencing average or higher levels of satisfaction.

#### 3.3.5. User experience

User experience encompasses the overall satisfaction and subjective experiences of users while interacting with the VR system. This metric includes emotional responses, perceived value, and the overall enjoyment of the VR training. Positive user experiences are crucial for the success and acceptance of VR-based training programs (Chandana et al., 2023). A study evaluating VR simulations for construction safety training found that participants experienced satisfying user experience and usability. The research focused on a VR simulation for the safe operation of hand-operated power tools, specifically an angle grinder. The results showed learning effects among participants, indicating that well-designed VR experiences can be effective for construction safety training (Strzałkowski et al., 2024). Another study explored a multi-player VR-based education platform for construction safety. This approach addressed the dynamic and teamwork characteristics of construction projects, which are often overlooked in single-user VR applications. The platform allowed for real-time monitoring of trainee performance and supported training performance analysis, demonstrating the potential of collaborative VR experiences in construction safety education (Luo et al., 2016). In conclusion, user experience plays a crucial role in the effectiveness of VR-based construction safety training. By focusing on key principles such as immersion, interaction, and realism, developers can create engaging and effective VR experiences that lead to better learning outcomes and improved safety awareness among construction workers.

In this project, the user experience for the developed safety training system was captured using the Presence Questionnaire (PQ) (Witmer & Singer, 1998; Ma et al., 2024). The PQ consisted of twenty-two questions to analyze five types of experiences: involvement, immersion, visual fidelity, interface quality, and sound. The questions in the PQ were categorized as follows: involvement (questions 1-7, 10, 13), immersion (questions 8, 9, 14-16, 19), visual fidelity (questions 11 and 12), and sound performance (questions 20-22). Each response in the questionnaire was prepared based on a 7-point scale (0-6). An average score of each category of PQ and an overall average score greater than 3 can be taken as acceptable for a VR system (Josh et al., 2021; Ma et al., 2024).

# Chapter 4. Experiment, Results, and Discussions

## 4.1. Experiment design and data collection

An experiment was designed to evaluate the developed VR-based safety training system, and the experiment process is shown in Figure 16. Approval for the experiment was obtained from the Institutional Review Board (IRB) under protocol number 22-083. All participants completed the SSQ for pre-screening to ensure their suitability (SSQ score less than 5) before starting the experiment. Participants then took paper-based tests on struck-by hazards (i.e., PPE usage and movement within a work zone with moving equipment) and performed two real-world heavy lifting tasks designed to evaluate ergonomics. A camera was installed in the room to record the box-lifting tasks. Afterward, each participant took the safety training in the VR system developed for this project. After completing the VR-based training, each participant retook the tests, i.e., paper-based questions for struck-by hazard and two heavy box lifting tasks for ergonomics assessment. Ten undergraduate students from the Mississippi State University were recruited for the project. Each participant took about 70 minutes to complete the experiment. Finally, participants submitted survey responses through Qualtrics that included questions about system usability, motivation, user experience, and simulation sickness (Gugssa et al., 2024).

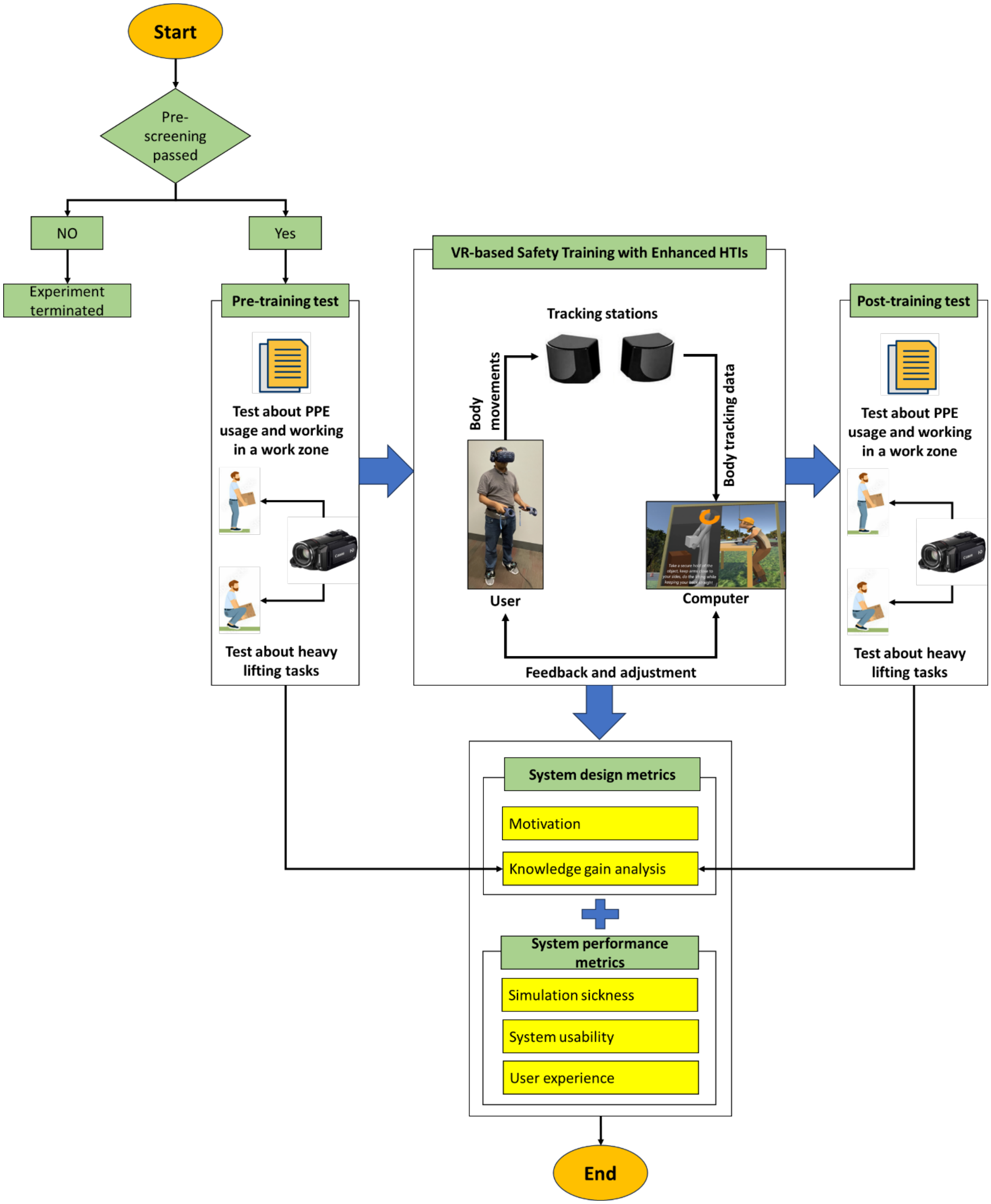



**Figure 16. Experiment process for the VR-based safety training**

## 4.2. Results of system performance assessment

### 4.2.1. Knowledge gain analysis

Figure 17 illustrates the average percentages of participants' knowledge gained in performance and compliance in safety-related tasks before and after participating in the developed training system. The tasks assessment included the use of PPE, working with moving equipment, lifting from waist level, and lifting from ground level (Gugssa et al., 2024).

The use of PPE showed that participants scored 33% in using PPE correctly before the training. However, this figure increased dramatically to 93% in post-training. This substantial improvement of 60% indicated that the training profoundly enhanced PPE usage among participants. Similarly, the training led to notable advancements in safe practices when working with moving equipment in the work zone. Initially, participants scored 33% in working with moving equipment correctly or safely. After the training, this percentage rose to 70%. This 37% improvement underscored the effectiveness of the training in instilling safer operational behaviors and reducing risks associated with struck-by hazards with moving equipment.

In the heavy box lifting tasks, participants also showed significant progress in their techniques for lifting from the waist level. Before the training, participants scored 74% in performing this task correctly. Following the training, this percentage increased to 90%, reflecting a 16% enhancement. The training also positively affected participants' lifting techniques from the ground level. The participants' percentage score of lifting correctly increased from 82% before training to 96% after training, indicating a 14% improvement.

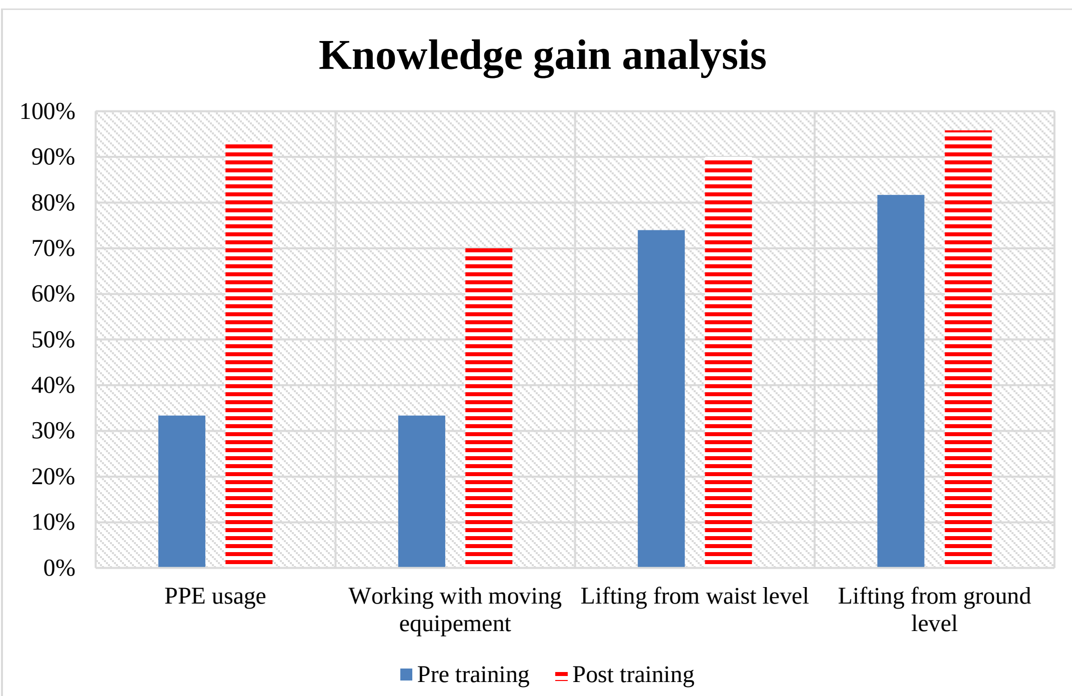



**Figure 17. Participants' knowledge gain after using the VR-based safety training system**

### 4.2.2. Motivation

The Motivation Questionnaire responses shown in Table 2 provide a statistical overview of responses to the motivational statements related to the developed training system (Gugssa et al., 2024). Table 2 shows the minimum, maximum, average, and standard deviation (SD) of the responses for each statement. Most of the responses ranged from 3 to 6, indicating that participants generally had moderately positive to very positive perceptions and attitudes toward the training program. The average scores for most statements were around 4.4 to 5.5, indicating that participants generally agreed or strongly agreed with the positive statements about the training. Higher averages, i.e., above 5 suggested strong confidence and positive expectations, while lower averages, i.e., closer to 4 still reflected generally positive but less intense agreement. The SD values (ranging from 0.67 to 1.20) provided insight into the consistency of responses. Lower SD values (ranging from 0.67 to 0.87) indicated that participants' responses were relatively consistent. Higher standard deviations (ranging from 1.10 to 1.20) suggested greater variability for items No. 1,6,7,8,10 and 11, indicating that participants had more diverse opinions on those particular statements. The results indicated that participants had a generally positive attitude towards the training program. They felt confident in their understanding of the training and had high expectations for applying what they had learned in the future.

**Table 2. Motivation score with statistical summary**

| Item No. | Motivation Questionnaire | Statistical Summary | | | |
|---|---|---|---|---|---|
| | | Min. | Max. | Average | SD |
| 1 | Compared with other volunteers in this training, I expect to do well in the knowledge exercise. | 3 | 6 | 4.7 | 1.10 |
| 2 | I am confident I understood the ideas explained in this training. | 4 | 6 | 5.5 | 0.67 |
| 3 | I expect to do very well in future practices. | 4 | 6 | 5.3 | 0.78 |
| 4 | I am sure I can do an excellent job on the problems and tasks assigned in the future like this. | 4 | 6 | 5.3 | 0.78 |
| 5 | Compared with other participants in this training, I think I know a great deal about the safety concerns in construction, especially for the work zone construction. | 4 | 6 | 4.8 | 0.75 |
| 6 | I prefer tasks that are challenging, so I can learn new things after taking training like this. | 2 | 6 | 5.2 | 1.17 |
| 7 | It is important for me to learn what is being taught in this training module. | 3 | 6 | 5.1 | 1.04 |
| 8 | I am highly interested in what I am learning in this training module. | 2 | 6 | 4.4 | 1.20 |
| 9 | I think I will be able to use what I learn in this training in other situations. | 4 | 6 | 4.8 | 0.87 |
| 10 | I think that what I am learning in this training is useful for me to know. | 3 | 6 | 4.7 | 1.19 |
| 11 | Understanding the safety protocols is important to me. | 3 | 6 | 4.9 | 1.04 |

## 4.3. Results of system design assessment

### 4.3.1. Simulation sickness

Table 3 shows the SSQ results for the developed VR-based safety training system, with scores and classification concerning the symptoms. A nausea score of 3.18 suggested that the participants experienced negligible nausea symptoms. An oculomotor score of 13.92 indicated significant symptoms, including eye strain, blurred vision, or difficulty focusing, reflecting a notable level of discomfort or impairment. A disorientation score of 6.19 implied minimal symptoms, indicating a minimum level of disorientation. Taking all aspects into account, the total score (6.65) for the developed training systems demonstrated minimal simulation sickness symptoms.

**Table 3. Results of simulation sickness analysis**

| Symptoms | Scores | Classification |
|---|---|---|
| Nausea | 3.18 | Negligible symptoms |
| Oculomotor | 13.92 | Significant symptoms |
| Disorientation | 6.19 | Minimal symptoms |
| Total score | 6.65 | Minimal symptoms |

### 4.3.2. System usability

The system usability results shown in Table 4 provide a statistical overview of responses to the system usability survey questions for the developed training system. Table 4 shows the minimum, maximum, average, and SD of the responses for each statement. The results obtained from the participants in this project indicated a total system usability score of 70.5. A total score above 68 indicates that users are experiencing average levels of satisfaction, which is preferable for the developed system.

**Table 4. System usability results**

| Item No. | System Usability survey questions | Min. | Max. | Average | SD |
|---|---|---|---|---|---|
| 1 | I think that I would like to use this VR module to learn and take safety training as a construction worker. | 1 | 4 | 2.90 | 1.22 |
| 2 | I would like to learn VR for other training purposes. | 1 | 4 | 3.20 | 1.08 |
| 3 | I found this VR module very easy to use. | 0 | 4 | 2.40 | 1.28 |
| 4 | The VR model helped me to establish the linkage between the protocols for construction safety knowledge and practice. | 2 | 4 | 3.40 | 0.80 |
| 5 | I found various functions (e.g., sound, videos, and control) in this VR module well integrated. | 1 | 4 | 2.90 | 1.04 |
| 6 | I thought there was too much inconsistency in this VR model. | 1 | 4 | 3.00 | 1.10 |
| 7 | I would imagine that most people would learn to use this VR module very quickly. | 1 | 5 | 2.70 | 1.19 |
| 8 | I think I would need the support of technical people to use this VR module. | 1 | 4 | 2.80 | 0.98 |
| 9 | I felt very confident using the VR module. | 1 | 4 | 2.60 | 1.02 |
| 10 | I should learn more VR-based knowledge before I use the VR module. | 0 | 4 | 2.30 | 1.27 |
| | | | Sum of averages | 28.20 | |
| | | | **System Usability Score = 2.5 x Sum of averages** | **70.5** | |

### 4.3.3. User experience

Table 5 presents a statistical summary of the responses to the user experience survey questions (i.e., the PQ) for the developed training system. Table 5 displays the minimum, maximum, and average score of the responses to each statement in the questionnaire. The scores of the different aspects covered in the PQ, including involvement, immersion, visual quality, interface quality, and sound, were all higher than the average score of 4. This indicated that the developed system's total average score of 4.65 was considered acceptable.

**Table 5. User experience results**

| Categories of PQ | Min. | Max. | Average Score |
|---|---|---|---|
| Involvement | 1 | 6 | 4.37 |
| Immersion | 1 | 6 | 4.12 |
| Visual quality | 2 | 6 | 5.05 |
| Interface quality | 2 | 6 | 5.10 |
| Sound | 1 | 6 | 4.63 |
| **Total average user experience score** | | | **4.65** |

## 4.4. Discussion

The system performance assessment indicated that participants' knowledge and motivation were significantly improved through the developed safety training. Participants showed substantial improvement in correctly using PPE, safely working near moving equipment, and performing heavy lifting tasks from both the waist and the ground levels. These improvements indicated that the training effectively enhanced participants' safety practices. The safety training resulted in a remarkable increase in correct PPE usage from 33% to 93%, demonstrating a 60% improvement. The safe practices with moving equipment increased from 33% to 70%. Moreover, the correct techniques for heavy lifting tasks improved by 16% and 14% for lifting from the waist and ground levels, respectively. These results emphasized the training's role in promoting safer behaviors among participants. Additionally, the motivation survey provided insights into participants' attitudes and perceptions towards the training program. The participants generally expressed positive attitudes towards the training, with average scores ranging from 4.4 to 5.5 across motivational statements. The obtained results indicated strong agreement with the training's effectiveness, relevance, and potential impact on their future performance. High average scores, i.e., above 5 on statements related to understanding the training content and expectations for future performance, suggested that participants felt confident in applying what they learned. However, higher SD values on certain statements indicated varying degrees of agreement among participants, suggesting areas for potential improvement in training delivery or content clarity.

The system design assessment focused on three main aspects: simulation sickness, system usability, and user experience. Participants reported minimal simulation sickness symptoms, with negligible nausea, significant oculomotor symptoms, and minimal disorientation. These results indicated that while participants experienced some discomfort related to eye strain and focusing issues, overall, the VR-based training system was acceptable regarding physical discomfort. The system usability survey indicated an overall system usability score of 70.5. This score suggested that participants found the system moderately easy to use and were generally satisfied with its functionality. The user experience survey provided insights into participants' perceptions of various aspects of the training system. Specifically, the involvement, immersion, visual quality, interface quality, and sound scores were above the average score of 4. The results indicated that participants found these aspects of the training system acceptable and satisfactory. In summary, the results suggested that the VR system with enhanced HTIs effectively engaged participants and provided a positive learning experience.

# Chapter 5. Conclusions and Recommendations

## 5.1. Conclusions

Existing VR-based safety training methods lack timely feedback and sufficient HTIs, which limits the effectiveness of training. Therefore, this project developed and evaluated a VR-based training system, focusing on the importance of HTIs in learning and engagement, to improve the effectiveness of work zone safety training. The developed VR-based safety training system contained training about two safety hazards - struck-by hazards and ergonomic risks, provided timely feedback to users, and enhanced HTIs during the training process. This project evaluated the developed system using system performance metrics, i.e., knowledge gain and motivation, and system design metrics, i.e., simulation sickness, system usability, and user experience. This project assessed knowledge gain by conducting experiments with participants and found significant enhancements in users' safety awareness across the safety hazard training scenarios. Additionally, the developed safety training system demonstrated above-average performance in several key aspects, including motivation, experience involvement, immersion, visual quality, interface quality, as well as sound quality. Moreover, the developed training system achieved minimal symptoms in simulation sickness and demonstrated positive system usability.

## 5.2. Practical implications and recommendations

The findings of this project have several practical implications for improving work zone safety training and also enhancing other safety training needs. The use of a VR-based safety training system has demonstrated the potential to significantly improve the training outcomes through knowledge gain, increased motivation, and an engaging training experience. These results offer promising ways for MDOT to implement training solutions that could lead to a safer work environment. Some key practical implications and recommendations from this project are presented as follows:

i. **Enhance the current safety training practices:** The outcomes of this project demonstrated that VR-based safety training with enhanced HTIs (e.g., near real-time feedback mechanism) can improve training effectiveness. MDOT could adopt VR-based systems with the feature of HTIs to train employees for enhanced safety awareness (not only limited to work zone safety training). Specifically, for the VR system developed in this project, considering it was tested on a small number of participants, MDOT could pilot this safety training system with a selected group of participants and assess the outcomes before implementing it on a full scale.

ii. **Customize training modules based on MDOT's needs:** The VR-based training system can be customized to simulate different workplace environments and tasks, making it a versatile tool for safety training. Leveraging advanced VR technology with enhanced HTIs, MDOT could partner with experts to create customizable training environments that reflect actual working conditions for the safety needs of MDOT. This will allow training systems to be more relevant to work types with higher safety risks and MDOT's safety needs.

### 5.3. Limitations and future research directions

Despite the positive outcomes, this project has some limitations and areas for future research:

i. **Sample size and participant diversity:** The sample size for the experiment conducted in this project is not large enough, and all participants were limited to MSU Civil Engineering students. Future research should include a larger and more diverse group of participants (e.g., real work zone workers) to validate the findings across different demographics (e.g., age).

ii. **Long-term effectiveness:** This project primarily assessed short-term knowledge gain and compliance. Future work could investigate the long-term effectiveness of VR-based safety training on safety practices and incident rates over time.

iii. **VR environment limitations:** Some participants in this project experienced significant oculomotor symptoms (although overall minimal symptoms for the system). Further research should explore ways to minimize these symptoms and improve overall comfort during extended VR use.

iv. **Content improvements:** Future work could improve the developed training scenarios and add more training content related to work zone safety to the VR system to address diverse learning needs and preferences and maximize engagement.

v. **Comparative studies:** Comparative studies with traditional training methods would provide more insights into the effectiveness of the developed VR training system, which is also a future research direction.

In conclusion, while the VR-based safety training system shows promise in improving workplace safety training effectiveness and engagement, further research is needed to address the limitations and explore the long-term benefits and broader applicability for the construction industry.

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