Analyzing the Impact of Virtual Reality and Haptic Feedback on the Safety Skills of Construction Workers

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Abstract: Emerging technologies are offering opportunities to address the gaps in traditional construction safety training. The idea of using interactive technologies such as virtual reality (VR) and haptic feedback (HF) has been gaining traction to provide targeted training experiences. Research from outside construction has shown VR to be an especially promising tool in enhancing learning experiences within occupational settings. However, there is no direct evidence that VR in conjunction with HF supports learning outcomes when paired with existing safety training paradigms. Therefore, this study tests whether combining VR and HF with traditional safety training approaches positively impacts the safety skills of construction workers. In an interventional experimental design, 221 employees from the construction industry were placed in a VR environment after receiving prerecorded video-based safety training. Linear mixed model analysis suggests that VR experience paired with passive training can improve hazard recognition performance of construction workers. Surprisingly, the VR experience as designed and tested in this study had a negative effect on participants' hazard recognition skills. However, there were no statistically significant changes observed in workers' risk perceptions, risk tolerance, and safety-related decision-making skills post intervention. Additionally, the study did not find evidence showing HF improves learning outcomes within VR experience. Although VR remains a promising platform for learning in occupational settings, this study suggests that more research is needed to better understand the contexts where VR enhances adult learning achievements in occupational settings. **DOI: 10.1061/JCEMD4.COENG-15981.**

Introduction

Many occupational health and safety (OHS) academics and professionals are looking to transform safety training by using virtual reality (VR) platforms. There are a number of reasons why VR-based learning interventions have generated so much enthusiasm. First, they permit workers to be placed in a complex dangerous setting that allows for them to gain situated learning without exposure to actual physical harm. Second, a growing body of evidence suggests that VR is effective in (1) enhancing creativity and curiosity (Garcia-Palacios et al. 2001; Wetzel et al. 1994), (2) sustaining long-term motivation to learn (Monahan et al. 2008; Yang and Goh 2022), and (3) improving knowledge retention (Burdea and Coiffet 2003). Despite the benefits, some studies have found that VR is not suitable for everyone because it can increase distractions (Parong and Mayer 2021) and cause cybersickness (Weech et al. 2019), which actively compromise learning. Additionally, it is unclear whether VR increases or decreases cognitive demand among learners (Lamb and Firestone 2022; Makransky et al. 2019). Therefore, the impact of VR on learning remains ambiguous.

Within construction, VR has been extensively used as an assessment tool to measure hazard recognition skills and risk-taking behaviors (Li et al. 2018; Perlman et al. 2014). A few studies have evaluated the efficacy of using VR for knowledge acquisition (Osti et al. 2021; Sacks et al. 2013), hazard recognition performance (Eiris et al. 2020; Jeelani et al. 2020), and promoting risk-averse behavior (Shi et al. 2019) but its application as a learning tool remains limited. Additionally, some of the aforementioned studies lack external validity because most of the evidence is gathered from limited data sets, sometimes consisting of only college students rather than adult learners. It is essential to conduct research on the targeted populations because the knowledge and experience of students, while seminal, may not extend to craft professionals and front-line construction workers. To address these knowledge gaps, the authors aim to examine the utility of VR as a learning tool for construction workers to practice safety skills. Specifically, a field experiment was designed to answer the question: *To what extent does VR-based safety training enhance situational awareness when paired with traditional training methods*? This foundational inquiry seeks to provide much-needed evidence before individual

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organizations make significant investments on the potential value-proposition of using VR technology in the construction industry as a platform for practice-based learning.

Additionally, the authors also sought to answer the question: *To what extent does haptic feedback (HF) during the simulation of a hyper-realistic accident inside an immersive VR experience enhance situational awareness?* HF can improve immersion of users in a VR environment (Kim et al. 2017); immersion has been found to be a key learning agent (Petersen et al. 2022) where higher immersion is positively correlated with improved learning outcomes (Huang et al. 2020; Weibel and Wissmath 2011; Yoon et al. 2015). This study examines whether these findings can be generalized to the construction industry. This inquiry may be helpful in practice where construction companies are considering the value proposition of using VR platforms with HF for training purposes.

Background

Endsley (1988, p. 97) defines situational awareness as, "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future." In the construction safety literature, the concept of situational awareness has been applied by Tixier et al. (2014) as: (1) recognizing the presence of a hazard, (2) judging the level of danger posed by the hazard, and (3) deciding how to behave around the hazard. This study focused on the three dimensions of situational awareness as distinct and critical safety skills.

Hazard Recognition, Risk Perception, and Risk Tolerance Skills

Based upon Haddon's (1973) energy release theory, Albert et al. (2017, p. 2) defined safety a hazard as, "a source of energy that, if released and results in exposure, could cause injury or death." To perform work safely, it is of paramount importance that construction workers be able to detect the energy sources (i.e., hazardous signals) around them, assess the risk associated with each hazard (i.e., risk perception; Hallowell 2010), assess their comfort around the risks as part of their job function (i.e., risk tolerance; Hunter 2002), and make a safety-related decision.

Most safety practices are created around the assumption that construction workers can recognize and respond to hazards appropriately (e.g., pretask planning, stop-work authority). However, experimental research has shown that workers can identify only an average of 46% of hazards when planning work (Albert et al. 2014a), which is explained by cognitive constraints associated with limited capacity for attention, fast (and sometimes irrational) processing of information, and intuitive decision-making (Hu et al. 2018; Kahneman 2011; Simons and Chabris 1999). Unsurprisingly, this is why minimal variability is observed in this baseline hazard recognition skill when controlling for worker experience, trade, and other individual differences (Hallowell 2021); poor hazard recognition skills is a generalizable phenomenon. To compound this problem, human beings are no better at quantifying risks and making decisions under risk when dangerous stimuli are identified. Research has shown that we are all highly susceptible to biased heuristics and emotional appraisals (Loewenstein et al. 2001). For example, Aranda and Finch (2003) found that, when safety measures (such as training sessions, protective gear, safety protocol implementation, etc.) are implemented on construction sites, workers feel safer and become overconfident about their skills and the surrounding environment, leading to their taking higher risks. Therefore, it is not reasonable to assume that construction workers would be inherently equipped with such critical safety skills which underscores the importance of safety training programs within the industry that need to effectively transfer this requisite knowledge.

Unfortunately, most safety training programs are based around learning environments that rely on one-way delivery of information which can be ineffective for adult learners (Merriam 2004). Additionally, most do not utilize the experiential and cultural background of workers, which results in suboptimal learning outcomes and negative appraisals of the training itself (Haslam et al. 2005; Wilkins 2011). This suggests that there are systemic limitations and issues with how workers are trained. Finally, there is no evidence to support that existing training programs are generating the requisite cognitive dissonance needed to alter deep-rooted perceptions, attitudes, and behaviors on a long-term basis. There is a critical need to revamp the design of training interventions toward more effective modalities that are applicable across disparate sectors and workforces within the industry.

In the past decade, the industry has found success through the introduction of mnemonic devices (Albert et al. 2014b), hyper-realistic practical demonstrations (Bhandari et al. 2019; Bhandari and Hallowell 2017), e-learning tools (Ho and Dzeng 2010), and computer-aided technologies (Gao et al. 2019) in improving the aforementioned critical skills. However, these teaching techniques and devices are highly context-dependent, their effectiveness for enhancing long-term learning remains unknown, and they function as piecemeal solutions (i.e., usually targeting only one of the aforementioned skills at a given time), all adding to the existing onerous training burdens. Thus, a needed intervention is one that holistically targets all three safety skills while also balancing typical job constraints (e.g., weather conditions, time availability, trainees' geographical location, trainee literacy, and language proficiency levels; Lin et al. 2017).

Using Virtual Reality for Safety Training

Virtual reality (VR) is a computer simulation that creates an image of a world that appears to our senses in much the same way we perceive the real world (Craig and Will 2009). Simply put, VR is an immersive digital simulation of our physical reality. Although early versions of the technology date to the 1950s, its popularity has greatly increased in recent years due to improved financial viability and hardware accessibility (Boas 2013). Industries such as medicine (Grantcharov et al. 2004; Seymour et al. 2002), aviation (Helmreich et al. 1999; Lee 2005; Rosen 2008), mining (Grabowski 2015; Grabowski and Jankowski 2015), and military (Lackey et al. 2016) have all started to utilize VR for personnel training. Indeed, VR has been shown to be a versatile educational platform in practice, capable of improving technical skills (Aim et al. 2016), aiding in stress and workload management (Lackey et al. 2016), and even fostering a more positive culture toward learning (Fussell and Truong 2022; Grabowski 2015; Grabowski and Jankowski 2015).

Table 1 provides a summary of key research studies that have evaluated the use of VR for construction safety learning and training. Collectively, the evidence demonstrates that VR-based safety training has promise in the construction industry. VR allows for simulation of operations and procedures, which can be used to educate novice workers and provide them with an opportunity to safely practice, explore, and fully understand their jobs prior starting work (Li et al. 2018).

However, practitioners must be cautious before accepting VR as the future of safety training because there are several gaps in the literature. Most studies have focused on testing VR in isolation from other interventions, which does not lend high ecological

Table 1. Summary of evidence from the construction industry on the use of VR to deliver safety training

Citation	Research goal	Findings
Yoo et al. (2023)	Identify the psychological antecedents and technological features that impact the effectiveness of VR-based safety training.	Study found that the telepresence and risk perception training greatly influence overall satisfaction with the training.
Yu et al. (2022)	Evaluate effectiveness of VR-based safety training for novice and experienced construction workers.	Study found novice workers received more benefit from VR-based training relative to experienced workers.
Nykänen et al. (2020)	Aimed to assess the efficacy of a VR-based safety training program.	Study indicates that VR has potential to increase safety competencies and foster motivational change.
Gao et al. (2019); Li et al. (2018); and Rey-Becerra et al. (2021)	Conducted a systematic literature review to understand the effectiveness of virtual technologies in construction safety.	VR systems are effective in improving hazard identification skills but not risk assessments.

validity to the findings. It is expected that VR for the foreseeable future would be used in conjunction with the traditional passive training, and it is important to understand how the two educational modalities would complement each other, if at all. Additionally, there is an assumption that detecting a hazard in the VR environment translates to real-world safety skills, which is an untested assertion to date. For these reasons, the authors tested the following null hypotheses:

1. Passive training paired with VR experience does not improve hazard recognition skills.
2. Passive training paired with VR experience does not increase risk perception.
3. Passive training paired with VR experience does not reduce risk tolerance.
4. Passive training paired with VR experience does not promote safe behavior.

Through experimentation, the authors sought to examine whether VR is an appropriate tool for practice-based learning among construction workers.

Using Haptic Feedback during Virtual Reality Training

Haptics refers to somatosensory devices that are meant to enhance a computer simulated experience (Robles-De-La-Torre 2006). Haptic devices artificially recreate various touch sensations to enhance communication interfaces between humans and nonnaturalistic experiences (Rakkolainen et al. 2021). Essentially, haptics are used to trigger our sense of touch to influence learning, attitudes, and behavior (Ackerman et al. 2010; Ernst and Banks 2002; Krishna 2012; Morris et al. 2007; Peck and Childers 2003). HF gives cutaneous and kinesthetic sensations (McGee 2002) that can decrease the demands on the working memory (Kiili 2005; Renkl and Atkinson 2003; Sweller 1988; Wickens 2002) and generate curiosity and interest (Jones et al. 2003) among individuals. In occupational environments, it is often used to support basic to highly complex motor skills (Feygin et al. 2002; Liu et al. 2006; Robles-De-La-Torre 2006) and make experiences less prone to memory corrosions by placing less strain on visual working memory (reduced cognitive load via visuo-haptic coordination) (Crandall and Karadoğan 2021; Mayer and Moreno 2003; Schönborn et al. 2011). For example, in the medical field, HF has been found to improve muscle memory and awareness of surgeons in training sessions by providing real-time feedback on errors (Bengtsson et al. 2003; Fabiani et al. 1996; Richard et al. 1996; van Asseldonk et al. 2009).

HF can be used to improve immersion experienced by users inside VR environments. While it is suggested in the literature that immersion through higher fidelity in a VR environment is beneficial (Gisler et al. 2020), it is unclear whether there is a point of diminishing returns. In fact, it is possible that visual, auditory, or kinesthetic feedback at some point could even generate excessive cognitive demand, thereby impeding a positive learning experience. Additionally, the concept of the uncanny valley, where very high fidelity simulations produce discomfort or eeriness among users (Mori et al. 2012), could further complicate the relationship between fidelity and learning effectiveness. To support the advancement of future cyber-learning experiences in occupational settings, it is important to determine the value of added fidelity (such as inclusion of HF) in improving the learning experience of adult learners.

Despite HF being regularly paired with VR to enhance user experience in many other industries, occupational training has seen limited use of haptic technology (Patil et al. 2018). It is unclear whether or not HF within VR-based safety training environments is a positive, negative, or nonimpactful learning agent. Thus, this study will isolate the impact of HF within the experimental design to determine whether HF is effective in improving the components of situational awareness above and beyond VR-based safety training. Given improved immersion in virtual environments can aid learning experience, the authors seek to test the following null hypotheses:

1. HF during VR experience does not improve hazard recognition skills as compared to VR experience without HF.
2. HF during VR experience does not increase risk perception as compared to VR experience without HF.
3. HF during VR experience does not alter risk tolerance levels as compared to VR experience without HF.
4. HF during VR experience does not promote safe decision-making behavior as compared to VR experience without HF.

Research Methods

Through a field experiment, this study aims to evaluate the extent to which VR-based safety training with HF supports traditional training designed to enhance hazard recognition, risk perception, and risk tolerance.

Development of VR Platform

To run the experiment, a novel VR simulation was created using the Unity game engine. SketchUp and Blender were used for 3D modeling, and immersive visuals and audio were delivered to the participants through the HTC Vive Pro VR headset. The VR environment was designed to simulate a typical pipeline construction project.

The authors elected to simulate the shack assembly process, which involves multiple shacks placed along the pipe joints to weld pipe sections together into one continuous pipe length. The shacks are transported and placed along the pipe joints using side boom cranes, and, once the shacks are lowered, welders enter them to weld the pipe joints. It is a process that continues across the entire pipe length until the pipe is ready to be placed into its designated trench.

An expert panel of six professionals working in the oil and gas pipeline industry, each with at least ten years of experience, was assembled to provide feedback during the design phase. They assessed the accuracy of the actual work processes, equipment, and overall *feel* of the jobsite. Based on their feedback, the research team was able to include and modify multiple features within the VR environment to enhance the ecological validity and immersion (Patil et al. 2018; Yoo et al. 2023). These features included visual elements such as personnel and motorized traffic, dust, terrain variability, vegetation, and climate variability, as well as audio elements such as social interactions between virtual avatars and construction noises. Furthermore, to replicate the naturalistic environment, movements of the virtual avatars were generated using the realistic body movements of actual human beings by utilizing Rokoko motion capture.

Two accident scenarios were also designed within the VR experience: *suspended load (i.e., welding shack) dropping from height* and *being struck by heavy mobile equipment*. These accidents happened to a virtual (i.e., fictional) avatar, not the participant. The simulation of the accident showed the events leading up to and including the point of energy transfer into a virtual avatar. The highly realistic recreations of accidents were aimed to generate targeted emotional arousal and engagement, both key antecedents to learning and memory (Bhandari et al. 2019). In this case, hyperrealism was achieved by implementing real construction sounds within the virtual environment and simulating realistic body movements in the injured virtual avatar by placing and recording amateur actors (viz., students studying theatre) in motion capture suits.

These accidents were also used to provide situated learning to participants by allowing them the experience of seeing the graphic consequences of uncontrolled hazards in a safe, virtual environment. Note that while the participants witnessed the accident, the authors elected to not simulate physiological impact from the accident on the virtual avatar (e.g., blood, screams) to minimize the risk of psychological harm to the participant or inadvertent minimization of realism. To support reflective learning, the participants (still in the VR environment albeit with paused simulation) were asked leading questions by the research team that required them to reflect on why the accident happened, the consequence of the accident, and how it could be prevented in the future (i.e., simulating root-cause analysis). The responses to these questions were not recorded for analytical purposes as it was deemed to be beyond scope, but future explorations can collect and examine qualitative data during learning experiences to provide richer insights into the antecedents to improved learning.

Experiment Protocol

Fig. 2 presents the experimental protocol implemented in this study. Each of the individual components of the protocol is elucidated as follows.

Passive Training Intervention

Participants were provided with a nine-minute training video providing a detailed explanation on the energy-based hazard recognition training. Energy-based hazard recognition training has been demonstrated in a number of field experiments to be efficacious in improving hazard recognition skills (Albert et al. 2017). On average, it was determined through multiple-baseline testing that this training intervention improves hazard recognition performance by approximately 30% (Albert et al. 2014b, 2013). For brevity, the authors refer readers to the citations provided for details on the training itself (e.g., Albert et al. 2014b, 2013; Hallowell 2021). The energy-based hazard recognition concept was introduced to participants via standardized video training to ensure that all participants received a homogeneous one-way delivery of information, thereby minimizing random noise.

Virtual Training Intervention

Before subjects entering the simulated worksite, the research team familiarized the participants with the VR equipment and space. To keep baseline instructions consistent, a three-minute introductory video was shown to all participants with instructions on what to expect in the VR environment and how to perform the task (i.e., take pictures to complete the safety audit). Once the VR equipment was placed on participants, they were taken to a generic virtual environment (bottom-left picture in Fig. 1), where they were asked to practice walking, turning, and taking photographs. A generic environment was selected to avoid any undue anchoring effects on participants' perceptions and/or learning experience. Participants were given the time to familiarize themselves on how to navigate space within the virtual environment, thereby reducing confounding effects of unwanted cognitive demands (Li et al. 2018). Once participants were acclimated and ready, they were allowed to enter the simulated work environment.

Since the purpose of this experiment was to examine the effectiveness of VR as a platform to practice the skills, a passive instructional activity was developed wherein participants were tasked with performing a safety audit within the VR simulation. For passive instructional activity, participants were asked to complete a safety audit. They were instructed to perform the audit for which they had to take photographs using a simulated tablet of all the hazards they observed within the virtual environment (Fig. 1). Upon receiving acknowledgement from participants that they had identified all the hazards, they received instructions to find the site's superintendent (i.e., virtual avatar wearing a green hard hat) and complete the task by handing over the virtual tablet. As soon as the participants handed over the tablet, one of the accident scenarios (*suspended load falling* or *struck-by incident*) noted previously was triggered.

Fig. 1. High fidelity VR environment of shack assembly operations in pipeline construction.

The accident simulated would correspond to whichever of the two hazards the participant failed to identify. If participants identified both hazards or neither, one of the two accident scenarios was randomly selected and triggered. When the participants identified one of the two hazards, the accident associated with unidentified hazard was triggered. During the simulation of the accident, the VR system would remove participants' autonomy to move about the virtual environment, thus ensuring that they witness the accident. As noted above, the simulated accident would pause at the point of energy transfer (i.e., avatar's physical injury was not simulated), at which point a facilitator would engage participants in a reflective learning exercise. Participants were asked the following questions while still immersed in the albeit paused environment:

1. Why do you think this accident happened?
2. What could have helped you identify this hazard? (*This question was asked only if the participant failed to see the hazard only)*
3. What would you do differently next time? and
4. What controls do you think the company should put in place to prevent the hazard?

The virtual experience was considered complete once all questions were verbally answered by the participants. Through this exercise, the authors sought to leverage adult learning principles including but not limited to giving the learners control over shaping their learning experience, formulating their opinions, and controlling the pace of learning with minimal guardrails and basic facilitation (Knowles 1977). In addition, the intervention leveraged Kolb's theory of experiential learning, which suggests that learning is a process that occurs thorough the transformation of experience (Kolb 2014). Kolb identifies four stages in this process: (1) concrete experience, or actively engaging in a new experience; (2) reflective observation, or reflecting on the new experience; (3) abstract conceptualization, or forming new understandings based on the reflections; and (4) active experimentation or applying what was learned to new situations. Thus, the VR experience designed here is intended to engage learners in this cyclical process of learning through a virtual experience, providing workers with a chance to engage in concrete experience, reflect and understand the accidents that occurred, and test their learning by repeating the process. In sum, the authors are examining the value proposition of using VR as a learning platform for workers to practice their skills in a risk-free environment.

Haptic Feedback

Participants were randomly divided into two experimental groups: VR-Only and VR+HF (Fig. 2). The former received only the VR experience as an intervention, and the latter received VR experience with HF. HF was activated whenever the accident was triggered. It was included to enhance the sense of realism by triggering emotional reactions and kinesthetic feedback to support learning (Pinzon et al. 2017). The vibrations from the haptic devices lasted a few seconds as the accident was simulated. It was not used at any other point to ensure ecological validity. In this experiment, HF was integrated using bHaptics hardware (controlled via bHaptics Player software), which included TactSuit X40 (for vibrational response on torso), TactVisor (for vibrational feedback on face), and Tactosy (for vibrational feedback on both hands).

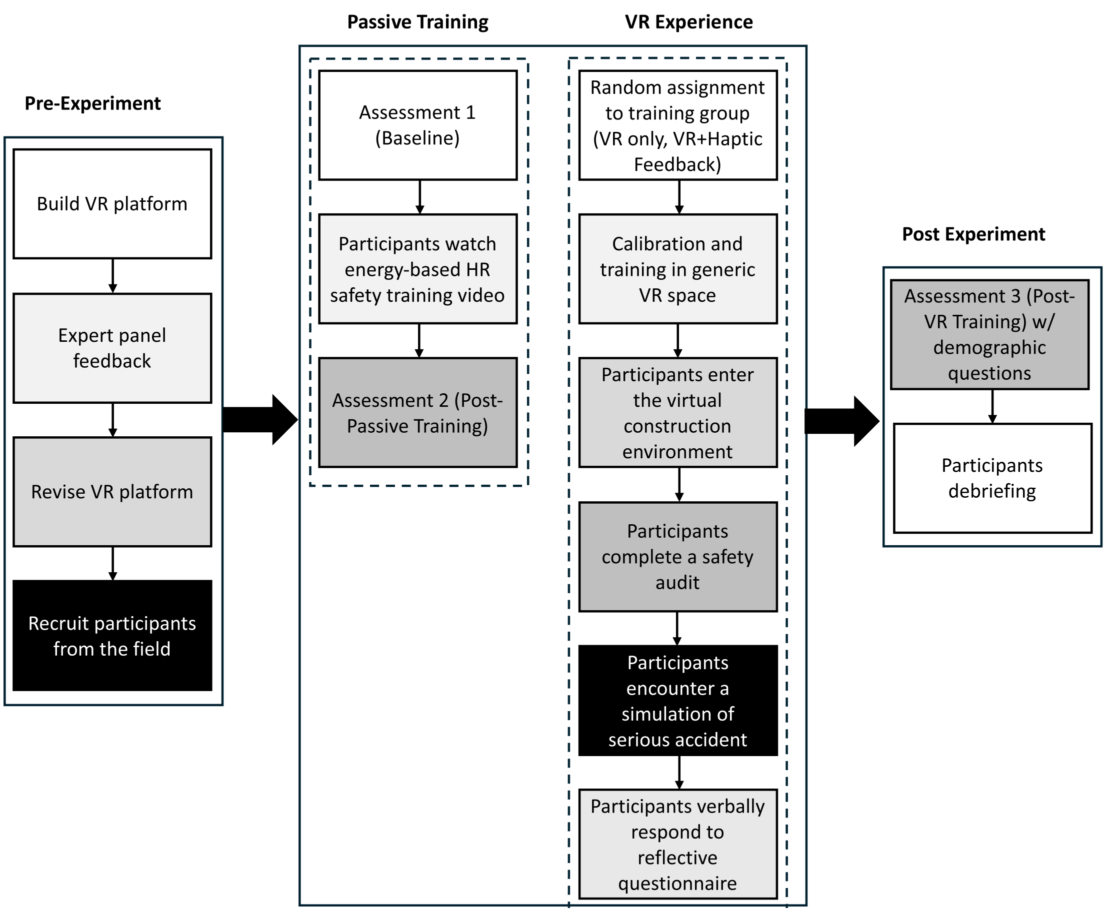

Fig. 2. Experimental protocol.

Assessments

Participants completed three assessments. The first (i.e., baseline assessment) was completed before any intervention was delivered. The second was conducted post-passive training to isolate the learning gains from the traditional training setup. Finally, the third was conducted post-VR experience, marking the final step of the experimental protocol (Fig. 2). This protocol does not allow the authors to determine the efficacy of the VR experience in isolation. However, it is possible in this experimental design for the authors to isolate the efficacy of HF, as participants were randomly placed in the control (VR experience with no HF) and treatment (VR experience with HF) groups.

All three assessments were identical barring two differences. The demographic information was collected only at the end of the third assessment (i.e., post-VR experience). Second, the pictures used in each assessment to measure hazard recognition, risk perception, risk tolerance, and safety decision skills were distinct. The pictures represented different construction work scenarios that participants needed to consider when responding to the questions. Each assessment contained the following subsections: hazard recognition, risk perception, risk tolerance, and safety decision, which are the individual components of the situational awareness model used within a safety context in the CEM literature (Tixier et al. 2014). Using a self-reported survey with a picture of a real construction site, participants were asked to consider the task and work environment depicted and identify all possible hazards. A total of three pictures were used in this experiment (one for each assessment phase, with mixed orderings between participants). The order of the three assessments was not randomized in the study; therefore, the authors controlled for the order in which participants saw the three pictures in the analysis.

To determine the hazard recognition skills of each participant, the authors divided the proportion of hazards identified by each individual by the total number of hazards present in the picture [Eq. (1)]. In Eq. (1), $HR_{picture}$ was the total number of hazards present in the picture (a summation of all the hazards identified by the participants and the research team of safety experts)

$$\text{HR Skill}_i = \frac{HR_{paticipant}}{HR_{picture}} \tag{1}$$

Risk perception and risk tolerance were measured on a 1-5 Likert scale, wherein participants were asked to consider the work being performed in the picture and the hazards they identified before rating *how dangerous is the work environment as shown in the picture?* (risk perception), and *how comfortable would you be working in this environment as shown in the picture?* (risk tolerance). Here, 1 represented *Not at all*, whereas 5 represented *Extremely.* These assessment approaches have been validated in previous studies (Bhandari et al. 2020). Finally, participants were asked to make a safety-related decision by considering the prompt *Consider the hazards in the photograph overall, would you stop the work at this job site?* on a scale of 1-5, where 1 represented *Definitely not* and 5 represented *Definitely yes*. This stop-work authority question was incorporated into the study to evaluate decision-making under risk. The surveys were conducted via a standardized online platform (i.e., Qualtrics) and each participant had unlimited time to complete each individual assessment.

Data Summary

A total of 221 construction industry employees participated in the experiment from across the United States. These included frontline works and site-leadership. The workers were recruited from nine different construction companies representing varying different sectors of the industry, including, but not limited to, commercial and infrastructure, oil and gas, and power generation and distribution. Table 2 shows the demographic distribution in the sample.

Table 2. Demographic distribution ($n = 221$)

Demographic dimensions	Subcategories	Participants (n)
Years of experience within the construction industry	0–10 years	133
	10–20 years	41
	20–30 years	23
	30–40 years	20
	40–50 years	3
	50–60 years	1
Witnessed injury	Has not witnessed an injury	93
	Minor (first-aid injury)	11
	Moderate (medical case but not life-threatening)	32
	Serious (lost worktime to recover from injury)	49
	Critical (disabling or fatal)	36
	Decline to respond	0
Been injured	Has not been injured	151
	Minor (first-aid injury)	21
	Moderate (medical case but not life-threatening)	20
	Serious (lost worktime to recover from injury)	25
	Critical (disabling)	1
	Decline to respond	3

The diverse sample from the target population lends high external validity to the findings presented below. But as with any quasi-experiment that is based in the field, the authors had limited control over the environment, reducing the internal validity. This study was approved by the Institutional Review Board at the University of Colorado Boulder. Participation in the study was completely voluntary and uncompensated. Participants had the option to complete the survey in either English or Spanish. Participation was restricted to employees primarily working in the field to heighten ecological validity. However, the following steps were taken to minimize measurement error:

1. The study environments were optimized for ventilation, temperature control, lighting, external noise, and disruptions.
2. The same facilitator interfaced with all the participants during experimentation to maintain a consistent and neutral demeanor.
3. A prerecorded video was provided during the passive training, ensuring standardized delivery of information for all participants.
4. The facilitator conducted surveys via a standardized online platform (i.e., Qualtrics).
5. Participants were briefed about the potential risks involved in the study protocol (e.g., cybersickness, headaches, disorientation, etc.), guaranteed anonymity, and given the freedom to withdraw from the experiment or refrain from answering any questions at any time in the study.

Results

According to the central limit theorem (CLT), regardless of the distribution of the source population, a sample estimate of that population's mean will have an approximately normal distribution if the sample size n exceeds 30 (Field 2013; Mascha and Vetter 2018). Thus, it is reasonable to treat the distribution of data collected in this study as approximately normal. For all tests, results were considered statistically significant at a confidence level above 95% (i.e., $\alpha = 0.05$). Subsequent sections detail the parametric tests employed to assess the study's hypotheses and their respective outcomes.

Hazard Recognition

To analyze change in safety performance due to the study's interventions, a paired-sample t-test was deployed. The interquartile range (IQR) technique was utilized to identify outliers in the hazard recognition scores of participants (Wan et al. 2014), revealing the presence of eight outliers (i.e., hazard recognition scores) that fell outside of the recommended 1.5 times the lower (25% percentile) and upper (75% percentile) quartile range (Walfish 2006). Following the recommendations of Vetter (2017), these outliers were removed from the data set.

Table 3 provides the grand means for the hazard recognition performance at every assessment phase of the protocol. A linear mixed model (LMM) analysis was used to determine the change in hazard recognition performance across different assessment phases. In this model, the subjects and pictures used in the assessments were treated as random effects. Satterthwaite approximations was used to approximate degrees of freedom. The results showed that change in hazard recognition performance was statistically significant when compared against Assessment 1 for both Assessment 2 (F [1, 423.9] = 67.1; $p < 0.01$) and Assessment 3 (F [1, 423.9] = 18.7; $p < 0.01$). This allows the authors to reject the null hypothesis and confirm that passive safety training combined with VR experience improves hazard recognition performance of construction workers. Overall, participants exhibited positive learning when compared against the baseline although the performance could be subject to confounding effects associated with participants' improved learning from repeated tests. However, the LMM analysis also confirmed there was a slight decline in hazard recognition performance from Assessment 2 to Assessment 3 which was statistically significant (F [1, 423.9] = 14.8; $p < 0.01$). This is surprising finding that warrants further future investigation.

Risk Perception

Table 4 shows the grand means for the risk perception performance at every assessment phase of the experimental protocol. The interquartile range (IQR) technique revealed no outliers in the analyses.

LMM analysis where subjects and pictures were treated as random effects revealed that there was no statistically significant change in risk perception scores in Assessment 2 (F [1, 422.3] = 0.21; $p = 0.64$) and Assessment (F [1, 422.8] = 0.60; $p = 0.44$) compared to Assessment 1. This does not allow the authors to reject the null hypothesis; passive training combined with experience in VR does not cause change in workers' sensitivity toward the risks posed inside construction environment. Finally, the difference in risk perception scores from Assessment 2 to Assessment 3 was not statistically significant (F [1, 422.3] = 0.095; $p = 0.76$).

Risk Tolerance

IQR technique revealed there were a total of 20 outliers; those observations (i.e., risk tolerance scores) were removed from the data set to minimize the noise within the analysis. Table 5 shows the change in grand means and the LMM analysis with subjects and pictures treated as random effects showed that there were no statistically significant changes in risk tolerance levels of workers.

Specifically, compared to Assessment 1, both Assessment 2 (F [1, 422.2] = 0.08; $p = 0.78$) and Assessment 3 (F [1, 422.2] = 3.33; $p = 0.068$) did not show significant change. Thus, the authors cannot reject the null hypothesis indicating the passive training and VR experience tested in this study does not alter construction workers' willingness to partake risk-taking behavior. As before, the change in risk tolerance scores from Assessment 2 to Assessment 3 was also not statistically significant (F [1, 422.2] = 2.37; $p = 0.12$).

Decision-Making Behavior

When applying the IQR technique to identify outliers for decision-making behavior, 61 outliers (i.e., decision scores) were identified and removed from the analysis. As shown in Table 6, the LMM analysis with aforementioned parameters showed no statistically significant change in decision-making scores of workers in Assessment 2 (F [1, 422.2] = 1.73; $p = 0.19$) and Assessment 3 (F [1, 422.2] = 1.61; $p = 0.21$) compared to Assessment 1. The difference in decision-making scores from Assessment to Assessment 3 was also not statistically significant (F [1, 422.2] = 0.002; $p = 0.96$).

Effect of HF

LMM analysis (where participants and pictures were treated as random effects and controlling for performance in Assessment 1 and Assessment 2) did not reveal statistically significant effects of HF

Table 3. Means for hazard recognition skill

Assessment phase	Mean (%)	Percent change
Assessment 1 (baseline)	15.0	—
Assessment 2 (post-passive training)	21.9	46.0%*
Assessment 3 (post-VR experience)	18.8	−14.2%*

Note: *Indicates statistically significant; N = 213.

Table 4. Means for risk perception

Assessment phase	Mean	Mean change
Assessment 1 (baseline)	4.04	—
Assessment 2 (post-passive training)	4.08	0.04
Assessment 3 (post-VR experience)	3.81	−0.27

Table 5. Means for risk tolerance

Assessment phase	Mean	Mean change
Assessment 1 (baseline)	2.30	—
Assessment 2 (post-passive training)	2.10	−0.20
Assessment 3 (post-VR experience)	2.71	0.61

Table 6. Means for decision-making behavior

Assessment phase	Mean	Mean change
Assessment 1 (baseline)	3.98	—
Assessment 2 (post-passive training)	4.12	0.14
Assessment 3 (post-VR experience)	3.75	−0.37

on any of the safety skills measured in Assessment 3 (*hazard recognition skill* $F[1{,}210.98] = 2.61$, $p = 0.11$; *risk perception* $F(1{,}210.99) = 0.01$, $p = 0.92$; *risk tolerance* $F(1{,}211.0) = 0.75$, $p = 0.39$; *safe decision-making behavior* $F(1{,}211.0) = 0.59$, $p = 0.44$). This is a noteworthy finding that demonstrates, compared against a control group (VR experience no HF), that HF did not deliver statistically meaningful changes in learning outcomes.

The results from Q-Q plot indicate that the residuals for all the models tested above are normally distributed, confirming that the model assumptions related to residual normality are satisfied.

Discussion

This study explores how situated learning experience provided to construction workers through a VR experience, paired with traditional training modalities and HF, impacts their safety skills. While the combination of passive training with VR experience improved hazard recognition skills of construction workers from baseline levels, the changes in risk perception, tolerance, and safe decision-making skills were not statistically significant. Surprisingly, there was a statistically significant decline in hazard recognition performance after workers received the VR experience compared to post-passive training. The decline could be because of the visceral experience of witnessing the accident and completing tasks in a novel immersive environment that suppressed workers' immediate hazard recognition performance. It is also possible that the HF devices themselves had an impact on the participants' focus, potentially because of discomfort or distraction from novelty of the system. Note, participants received the self-report right after each learning experience (i.e., passive training, VR-based training) without any breaks. It is possible that there was exhaustion-related effects post-training (e.g., motion-sickness, cognitive load) that impeded workers from demonstrating learning outcomes. On the other hand, it is also possible that the unguided learning experience within the VR environment was determinantal to learning outcomes of adult learners in occupational settings (Brookfield 1986). Efficacy of self-directed learning is dependent on the context in which it is used and learners' personal disposition toward learning the information being shared. Finally, some participants may be unfamiliar with work environment simulated within the VR experience, which could have resulted in noise within the data associated with undue cognitive demand or confusion during the VR experience. Although, the nature of hazards across construction sites and sectors remains consistent (e.g., suspended loads, heavy mobile equipment, powered tools, traffic), more research is needed to provide confirmatory evidence around the value proposition of using VR for safety training purposes.

The training did not reveal changes to workers' risk perception (or sensitivity toward the risks), risk tolerance, and safety decision-making skills. This suggests that while energy-based hazard recognition training validated in previous studies could improve hazard recognition performance of workers, it does not necessarily make them risk-averse. Additionally, the VR experience simulated only a couple of specific accidents. The results suggest that such emotionally evocative albeit specific experiences (e.g., Bhandari et al. 2019) may yield sensitivity toward specific risks but does not increase the levels risk assessed across different hazards, reduce willingness to partake risky activities, and promote risk-averse decisions among construction workers. While research suggests that instilling emotional heuristics could promote overall risk-averse behavior (Finucane et al. 2000), further research is needed to understand how those design and deliver such cues within safety training environments.

Finally, the incorporation of HF, envisioned to enhance the engagement within the VR experience, did not yield the anticipated benefits in improving hazard recognition, enhancing risk assessment, or fostering safer decision-making behaviors. The evidence presented here suggests it may be reasonable to assume that immersion within virtual environments have a diminishing return on increased immersion in VR environments. While immersion and increased presence within VR environments is critical, the relevance of immersion may depend on the audience and context of VR usage. This also suggests that some of the findings reported in the engineering education literature (e.g., Asghar et al. 2019; Satapanasatien et al. 2021; Valentine et al. 2021) may not generalize across adult learners in nontraditional classroom learning environments, such as occupational training. Further investigations are needed on how to tailor the immersive features within the VR-based environments for construction workers.

Limitations

Despite its strengths, the present study faces some limitations. First, the VR environment only simulated the welding process used on pipeline projects. Construction work is highly heterogenous across sectors and pairing workers with unfamiliar with work environments may have suppressed their learning achievements. Second, the VR experience only simulated two high-impact accidents to demonstrate the consequences of high-risk hazards. Future work should consider designing and delivering learning experiences that simulate a suite of accidents for workers for a comprehensive learning experience. Third, additional assessment strategy need to be considered within the OHS literature. It is possible that the training provided to participants in the VR environment did not sufficiently prepare them to demonstrate knowledge in self-report surveys with static images. Future studies should examine impact of typical assessment instruments used within safety literature to measure to understand the features associated with its content validity. Fourth, limited feedback was provided to participants during the immersive experience making it a less guided learning environment despite deploying a multimedia learning experience. This was done to explore the intrinsic value of VR-based learning experience where workers got an opportunity to practice safety-related concepts they learnt from traditional learning modalities. Future studies could explore how real-time feedback can be incorporated within VR environments to provide targeted instruction (e.g., feedback on hazards identified, missed, risk profile of hazards present in the environment etc.). Fifth, the assessments in this study are confounded by time and unavoidable learning from repeated similar tests. Future studies should examine impact of typical assessment instruments used within safety literature to measure to understand the features associated with its content validity. Sixth, the removal of 61 outliers (27% of the data) for decision-making behavior was necessary to ensure the robustness of the analysis. These outliers, identified using the interquartile range (IQR) method, represented extreme values that could disproportionately influence the results. However, the substantial proportion of outliers highlights potential limitations in the assessment tool or experimental protocol. Future studies should refine these tools and explore alternative methods for handling extreme values to minimize data loss and ensure the validity of the findings. Seventh, the study's focus on pipeline construction projects may limit the generalizability of the findings to other construction contexts. Future research should investigate the effectiveness of VR+HF across a broader range of construction environments to enhance external validity. Additionally, variations in the tools and metrics used to measure outcomes, such as risk perception, tolerance, and decision-making, could contribute to differences in results across studies. Future work should prioritize the development and validation of standardized assessment tools to ensure comparability of findings across contexts. Eighth, the timing and duration of the VR+HF interventions may have influenced the outcomes. The relatively short exposure to VR, while common in construction safety training, may not be sufficient to alter deeply ingrained behaviors or perceptions. Future research should consider longer intervention periods or follow-up assessments to explore potential delayed effects of the training. Finally, the quasi-field experimental design did not allow the authors to draw conclusions about the effectiveness of the VR experience in isolation; rather, the authors were only able to provide evidence regarding the combined effectiveness of video-based training and subsequent VR-based learning experience. In this field-based study, the authors did not want to deprive workers from the VR-based learning experience which is why a control group was not included. Future research could not only perform a controlled experiment but follow a controlled research design that allows for causal inferences.

Conclusion

There is a strong case to be made that adult learners would benefit from the adoption of technologies such as VR in occupational learning environments. Mounting evidence suggests that technologies such as VR and HF can assist adults in learning technical information and enhancing fine motor skills. For these reasons, many practitioners are excited to use VR for training to give their frontline employees the simulated experience of risks without causing any physical harm. However, this study shows that VR and HF may not be as universally effective at improving safety performance as some have hypothesized. While there was improvement in hazard recognition performance overall from the intervention (video-based training paired with VR), there was a decline in the immediate performance measured post-VR. Additionally, the intervention did not an immediate impact workers' risk perception, risk tolerance, risk-averse decision-making skills. Therefore, further research is needed to investigate the how, if at all, should VR-based platforms can be integrated with traditional training modalities (e.g., video, lectures). Understanding the limitations and proper application of VR and HF will help practitioners to design cost effective safety training initiatives for the future.

Data Availability Statement

Data generated or analyzed during the study are available from the corresponding author by request. Information about the Journal's data-sharing policy can be found at: http://ascelibrary.org/doi/10.1061/(ASCE)CO.1943-7862.0001263.

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