Process and Outcome-based Evaluation between Virtual Really-driven and Traditional Construction Safety Training

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Abstract

The emerging digital technologies such as virtual reality (VR) provide an alternative platform for construction safety training. In order to explore how digital-driven technologies affect the effectiveness of safety training, there is a need to empirically test the differences in performance between digital 3D/VR safety training and traditional 2D/paper approach. This research conducted a performance evaluation that emphasises both the training process and learning outcomes of trainees based on researchers' self-developed immersive construction safety training platform. Data related to physiological indicators such as skin resistance were collected to measure safety performance before and after the training. The detailed measurement indicators included nine categories (e.g., immersion, inspiration) to form a holistic list of evaluation dimensions. The findings revealed that VR-driven immersive safety training outperformed the traditional way for trainees in terms of both process and outcome-based indicators. Results confirmed that safety training was no longer constrained by understanding or memorizing 2D information (texts and images). Instead, trainees experienced a stronger sense of embodied cognition through the immersive experience and multi-sensory engagement by interacting with the VR-driven system. By engaging the theory of embodied cognition, this research provides both the empirical evidence and in-depth analysis of how immersive virtual safety training outperforms traditional training in terms of both training process and outcomes.

Keywords: construction safety; embodied cognition; safety training; virtual reality; immersive technology; hazard recognition

1. Introduction

Construction industry faces significant challenges including safety issues, in terms that construction has the highest number of injuries crossing all industries (Adami et al., 2021). Safety training can enhance workers' safety awareness and capability of handling danger (Williams et al., 2010), and is considered a key approach to reduce safety risks. Existing safety training mainly relies on traditional techniques such as lecturing, toolbox meeting, and video or textbook learning. One of the significant limitations is that it is difficult to fully engage workers in the learning environments created by these traditional techniques. Trainees could have limited engagement in a passive learning mode. The information capturing for further processing and forming longer-term memory of safety scenarios could be hampered due to lack of interaction and insufficient site experience. Learning by doing does have pedagogical values. However, educating workers by placing them into hazardous real-life jobsites is expensive and unethical.

The technological evolvement in the era of Industry 4.0 has enabled a highly immersive and interactive experience for learners. Construction safety training has also been involved with the adoption of emerging digital technologies such as virtual reality (VR). Existing studies (Eiris et al.,2018; Nykänen et al.,2020) adopting virtual or immersive technologies for construction safety training were largely limited to training outcomes or trainees' subjective evaluation of these technologies, but lack the comprehensive or empirical evidences to evaluate the effectiveness of immersive technology as compared to the traditional training mode. The other limitation from existing VR-driven studies (e.g., Tao et al., 2019) is that they had been limited to a single feature of VR, such as immersion, but without a more comprehensive evaluation of other features, for instance, first-person experience, degree of fun, and interaction, etc, all of which are essential components of gamification (Mouaheb, et al. 2012) and can increase player/user participation and engagement during learning (Landers, 2014). There has been insufficient investigation based on a multi-criteria framework to evaluate the effects of VR for safety training. Furthermore, the mechanism of learners' cognitive process in the VR-driven training, especially how it differs from the traditional training, has been underdeveloped.

Several prior studies (e.g., Li et al., 2021; Zhang et al., 2021a) applying VR for safety-related training crossing industries. It was believed by Adami et al. (2021) that previous studies adopting VRs for training purposed had not sufficiently engaged learning theories but simply technical aspects of the prototypes. VR could more effectively engage learners with bodily experience, which is widely lacking in traditional learning environments. It is theoretically hypothesized that adopting VR in safety training could enhance the training effectiveness by increasing learners' embodied engagement. Embodied learning is viewed as educationally significant based on facts that the individual should be treated as a whole being to be permitted to experience themself as a holistic, synthesized, acting, feeling, thinking being-in-the-world, instead of being separated between physical and mental activities (Stolz, 2015). It was confirmed that the heuristic role of immersion in VR is linked to educational affordances such as empathy and embodied cognition (Shin, 2017). There is a need to explore how embodied cognition plays a role in VR-driven construction safety training.

This study investigates the mechanism that causes the differences between VR-driven and traditional training for construction safety. Both objective and subject data are collected in the empirical study. Objective data are based on: physiological reactions of learners or trainees during the training process; and the task performance following training by recognising safety hazards. Subjective data are collected using a questionnaire following each individual's VR-driven experiment to measure the effectiveness of the training process and the follow-up impacts in a multi-criteria indicator system. This study echoes Adami et al. (2021) that theoretical background should be engaged in applying VR rather than technical aspects alone. The novelty of this study lies in that: (a) it deploys both objective and subjective data collection approaches; (b) it engages both process and outcome of safety training in evaluating the effectiveness of VR-based training of safety hazard recognition; and finally (c) it further employs the theory of embodied cognition to conduct an in-depth qualitative analysis of how VR-driven training differs from the traditional training of construction safety in terms of effectiveness. By addressing the question of how VR as the alternative platform affects training process and outcomes, the findings of this study provide both empirical and theoretical guides for construction industry in adopting VR or other immersive technologies for safety training.

2. Literature Review

2.1. Individuals' recognition of construction safety hazard

Safety perception is considered a key proactive indicator in construction safety management (Chen and Jin, 2013). It consists of perception towards site hazards (Han et al., 2019a). Hazard recognition of individuals engages mental activities and cognitive load (Han et al., 2021). Understanding the mental representations used for hazard recognition helps developing inspection strategies for effective safety management (Chong et al., 2021). Early-stage intervention is one method to improve the hazard recognition performance of construction employees (Albert et al., 2014). The training of hazard detection or recognition is widely adopted as the early-stage intervention aiming to improve workers' safety performance (Albert and Routh, 2021). Traditional training of hazard recognition in construction includes observing images. These images could be static, partially animated, or fully animated (i.e., video) as studied by Eiris et al. (2021). The experimental comparisons of the effects of three different image types on hazard recognition revealed no significant differences in training effectiveness in terms of individuals' positive attitudes, engagement, and sense of being transported to the scenario location (Eiris et al., 2021). Albert and Routh (2021) proposed specific training intervention elements that could result in superior safety performance and outcomes, including integration of visual cues to guide hazard recognition, immersive experiences in virtual environments, personalization of training experiences, and testing and feedback, etc.

Prior studies (e.g., Chen and Jin, 2013; Han et al., 2019a) had widely adopted a questionnaire survey approach to ask construction employees to self-evaluate safety hazard-related perception. The questionnaire survey approach alone suffers from the drawback that participants may lack situational engagement through site-based scenarios when filling the questionnaire (Han et al., 2021) with potential consequences of relying on their memory. Emerging digital and visualisation technologies with an experimental approach such as eye-tracking wearable devices (Chong et al., 2021) can fulfil this limitation. Combining the traditional questionnaire survey with digitisation-driven experiments can be found in several studies from recent years studying influence factors on hazard recognition performance, such as Han et al. (2021) and Kim et al. (2021). These influence factors on hazard recognition include personal traits (e.g., prior site experience) as found by Hasanzadeh et al. (2016), site conditions such as lighting (Han et al., 2020), and task mode of employees (Han et al., 2021). These aforementioned studies (e.g., Bhoir et al., 2015; Hasanzadeh et al., 2016) recruited students with similar academic and practical experience as participants in experimental research adopting digital devices for safety performance measurements. The rationale of recruiting university students instead of site employees was justified in Han et al. (2020) and

Comu et al. (2021), i.e., to exclude the effects of personal traits and to focus on the studied variable or influence factors.

2.2.Digitalisation-driven immersion training

VR allows users to create, explore, and interact within environments that are perceived to be nearly reality (Repetto et al., 2016). VR-based safety training provides a promising alternative to the traditional passive training approach (Nykänen et al., 2020). Izatt et al. (2014) described the visualisation technology with an interactive VR-based platform and stated that the user interface was suitable for physics education. Using a virtual platform for training firefighters' on wayfinding in search of victims in a burning building, Shi et al. (2021) found that the virtual platform added value by allowing firefighters to experience disorientation and use their existing knowledge to find victims in an unfamiliar building. Also applying VR for emergency evacuation such as under fire, Zhang et al. (2021b) discussed the value of VR in complex building path planning in terms of evacuation simulation. Applying VR platform for construction pipeline operation training, Shi et al. (2020b) found that compared to trainees recalling information from 2D drawing, those trained through 3D and VR outperformed in operation tasks. By adopting a 360-degree panorama virtual training environment for fall hazard recognition, Eiris et al. (2020) found that safety immersive storytelling provided an analogous outcome compared to the traditional training, with reduced time required and a stronger sense of presence for trainees. So far, there has been limited amount of empirically in-depth research on adopting immersive and interactive VR platform in construction safety training, specifically, on how the visualisation technology affects the training effectiveness of recognising site hazards. The training effectiveness could be measured by both process (e.g., cognitive mechanism), and outcomes such as task performance as measured by Shi et al. (2020) in construction operational training.

2.3.Embodied cognition

Embodied cognition is a cross-disciplinary (e.g., neuroscience, psychology) terminology following the assumption that the body functions as a constituent of the mind rather than a passive perceiver and actor serving the mind (Leitan and Chaffey, 2014). Bodily states and modality-specific systems for perception and action underlie information processing, and the embodiment contributes to multiple aspects and effects of mental activities (Foglia and Wilson, 2013). It is a proposed theory in cognitive science that cognition is embodied (Wilson and Golonka, 2013). Prior experimental studies claimed that cognition is influenced by the body states (Eerland et al., 2011), and the environment (Adam and Galinsky, 2012). It is stated that the abstract cognitive states are grounded in the states of the body (Miles et al., 2010). Kilteni et al. (2012) proposed that the sense of embodiment consisted of three subcomponents, namely sense of self-location, sense of agency, and sense of body ownership. Consequently, VR was suggested as a means to enhance the sense of embodiment through the three subcomponents by Kilteni et al. (2012). In this regard, the immersive environment created by VR works as the self-location; VR-based user platform or interface serves as the agency; and users' physiological reactions reflects the body engagement.

VR offers immersion, embodiment, and presence through gaming (Evans and Rzeszewski, 2020). It has been found that immersion in a VR-based game setup increased users' psychological arousal (Yao and Kim, 2019). Awada et al. (2021), by applying VR experiments in shooting studies, found out that VR induced emotional arousal and increased users' heart rate. The study of Steidl et al. (2011) on cognitive skill learning suggested that emotional arousal could in parallel, enhance the neural systems that support procedural learning and its declarative context. Shim (2018) investigated the user experience in VR by exploring the immersive storytelling context in a VR model that integrated presence, flow, empathy, and embodiment. It was suggested that the cognitive processes were significantly correlated to users' empathy and embodiment. In the VR-driven learning environment, Shin (2017) found out that embodied cognition process is shaped by learners' perception and context. The study of Shin (2017) laid the foundation for VR technologies as a heuristic assessment tool for a user embodied cognitive process.

3. Methodology

This research was based on the comparative studies of safety training performance adopting two different approaches, namely the VR-driven immersive training and the traditional textbook learning. The training performance was measured by learners / trainees' recognition of safety hazards in given construction site scenarios. The research team self-developed the whole VR-based immersive training system that underwent trials and tests as seen in the workflow of the study described in Figure 1. According to Figure 1, this study was divided into three major phases. In the first phase defined as pre-experimental preparation, the safety hazard scenarios were obtained by the research team from real-world construction sites. The research started from establishing safety hazard scenarios, which would be assigned to both groups of trainees, i.e., traditional textbook learning in a classroom, and the VR-based immersive safety training; in the second phase defined as comparative training, the two groups of trainees were arranged in a parallel way to receive their safety training, but underwent consistent monitoring before, during and after the training. Three major measurements were taken for each trainee, namely physiological reaction during training in terms of skin resistance, learning performance measured by hazard identification, and self-reflection by filling a post-training questionnaire; in the third phase defined as post-experiment analyses, the three major measurements enabled comprehensive comparisons of the two different safety training approaches, and further exploration by embedding the Embodied Cognition Theory defined in Foglia and Wilson (2013).

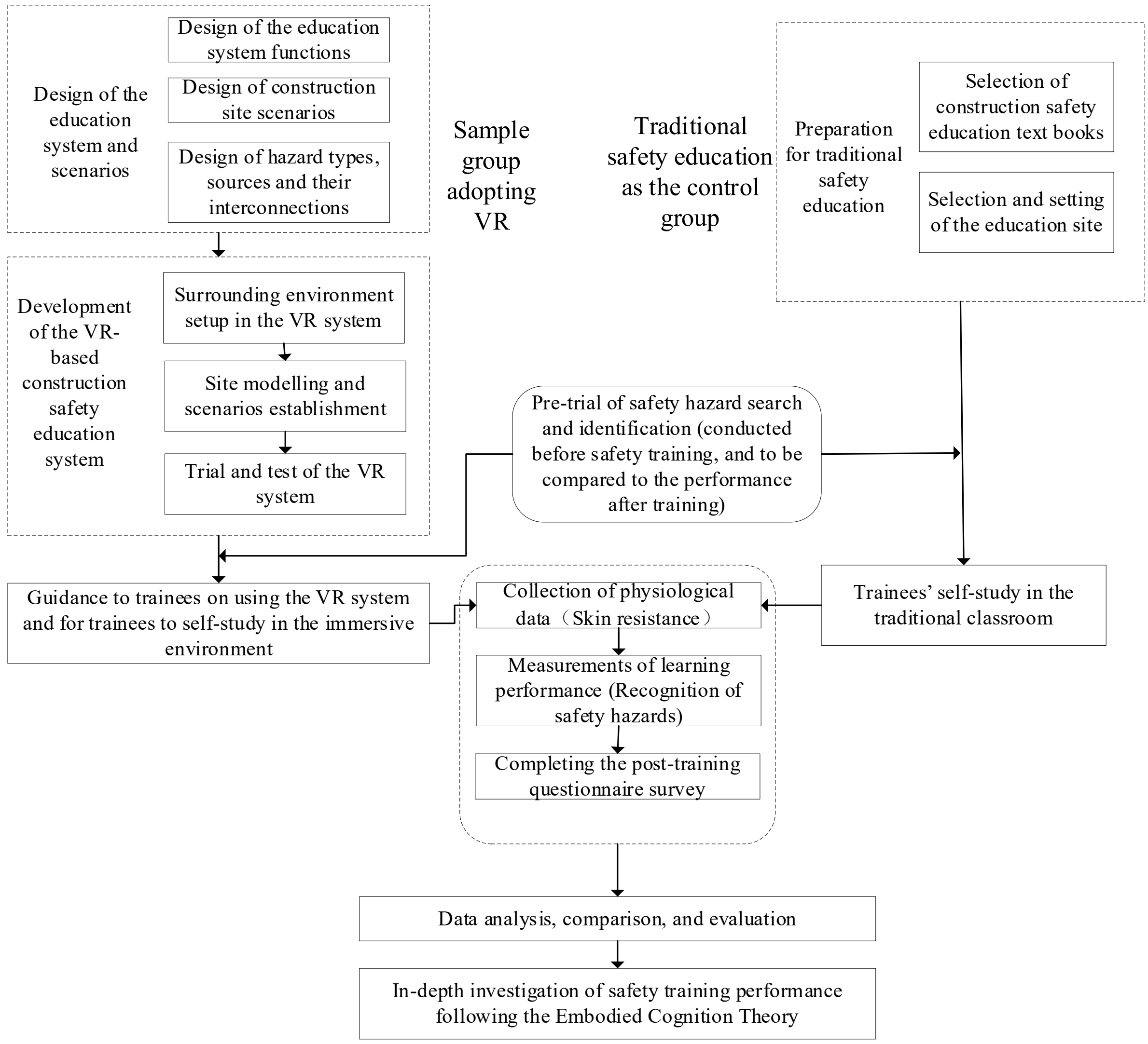


Figure 1. Workflow of the research

3.1.Experimental measurements

This experimental study measured the safety training effectiveness based on both the training procedure and endpoint performance by comparing the two aforementioned approaches. Four major dimensions were defined to compare the training effectiveness between VR-based immersive training and traditional training, namely self-evaluation of learning process, endpoint evaluation of learning impacts, physiological reaction, and learning performance.

The learning process and learners' endpoint evaluation were measured through a post-training questionnaire, involving a total of nine indicators. The learning process was measured by seven indicators, namely openness, flexibility, immersion, ease of learning, comfort, interactive engagement, and degree of fun. These indicators were generated from emotional dimension related theories (Schmid K et al., 2011; Steidl et al., 2011; Jhean-Larose et al., 2014), which describe that highly fluctuating emotions can keep the human brain at a high level of arousal and that the high arousal could enhance the learning effects. These seven indicators were used to measure individual trainees' evaluation of the learning environment and manners. Endpoint evaluation of learning effects was defined by the proactiveness and degree of inspiration, which was defined to measure the effectiveness of the training approach on driving the learning desire.

Existing studies (e.g., Deng et al., 2012; Zhao et al., 2021) indicated that several physiological indicators such as skin resistance, respiratory data, heart rate, pulse rate, and body temperature could reflect human beings' mental status. Among these indicators, heart rate, pulse data, and respiratory value are consistently related to the individual's nerves and significantly affected by the individual's ability to tolerate mental stress (Yang, 2021). Skin resistance is a physiological indicator to expressly evaluate an individual trainee's mental status. According to Ye (2021), skin resistance changes are caused by: 1) variation of human body's sweat secretion rate due to external environmental and physical emotional stimulus, and 2) changes of contraction and relaxation of blood vessels caused by nervous system activity. Compared to other physiological indicators such as blood pressure, heart rate and body temperature, skin resistance is more sensible to individuals' mental status variation (Steinberger et al., 2017). It is significantly affected by emotional status and linearly related to the level of emotional arousal (Shi, 2017). Emotional arousal would result in noticeable skin resistance change (Bradley and Lang, 2000). Therefore, skin resistance is often adopted as a physiological indicator in emotional arousal experiments (Reimer & Mehler, 2011). This research adopted skin resistance as the measurement for trainees' emotional arousal.

Finally, the learning performance was measured by the performance changes of recognising safety hazards before and after the safety training. The two indicators in terms of accuracy and time spent in detecting safety hazards were adopted for measuring the learning performance.

3.2. Experimental setup

Two approaches to safety training were provided for the comparative study as shown in Figure 1. The VR-based immersive training was designed as the alternative to traditional textbook-based learning. The procedure of the VR-based training system developed by the research team as illustrated in Figure 2, was comprised of multiple aspects of the immersive engagement process, including virtual construction site tour to search hazards, identifying hazards, hazard analysis and evaluation, reaction and decision-making in response to hazards, and individual performance being recorded. As seen in Figure 2, any of the steps related to hazard detection, analysis, or reaction would cause virtual safety accidents.

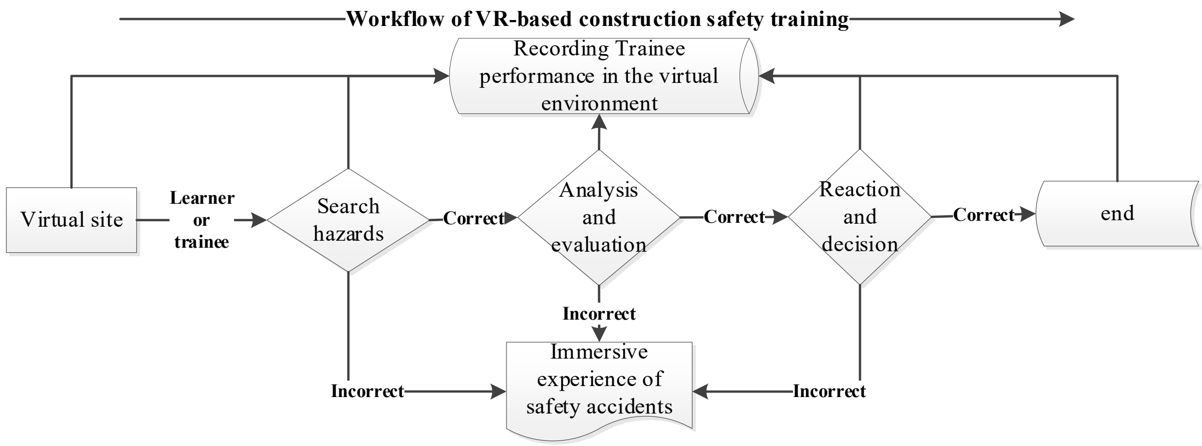


Figure 2. Procedure of the VR-based construction safety training

Extending from the previously developed virtual safety training platform (Han et al., 2021) by the researchers, the three hazard-related activities causing immersive accidents illustrated in Figure 2 can be further demonstrated by using the fall from uncovered hole as an example. In the VR-based training platform, trainee must first click “Yes” to correctly identify the hazard when the uncovered hole is seen. Then the trainee is asked to answer two questions at the analysis and evaluation stage towards the identified hazard, i.e., what is the danger level of the hazard, and what types of accidents could result from the hazard. Finally, the trainee is required to make a decision to handle the hazard, such as “remind myself on this hazard”, “wait around the hole and inform others passing by”, and “report it to the site safety staff”, etc. These questions and decisions are provided in the VR platform in the form of multi-choice options. The responses or answers selected by the trainee are then recorded as task performance. The VR system automatically evaluates and scores the individual trainee’s task performance, so the trainee is provided with the feedback afterwards. The VR-based immersive training system described in Figures 1 and 2 and shown in Figure 3 was supported by these hardware sets, including: Dell G7 laptop; HTC Vive VR headset developed (HTC Corporation, 2020); VIVE EYE PRO; and Avatars. Additionally, HKR-11C+ sensor shown in Figure 4 was adopted for measuring the skin resistance signal change. The sensor, with a range from 100K to 2.5M, measurement accuracy at 2.5K, and error at +/-2%, met the technical requirements for this study.

Figure 3. VR experimental system

Figure 4. Skin resistance sensor

3.3.Experimental participants

Experimental participants were recruited from Jiangsu University students in the disciplines of construction management or civil engineering but with little site experience. Random sampling procedure and methods were adopted as consistent in the earlier studies conducting immersive-based safety hazard recognition tests (Han et al., 2020b; Han et al., 2021), which also recruited students from the same disciplines. This rationale of recruiting students only instead of other participants from different backgrounds could be justified by Comu et al. (2021) that different participants, as affected by their field experience, education and site role, would perform significantly different in safety training. In this study, participants were divided into two groups, namely traditional safety training and VR-based immersive training. Recruiting university students instead of construction professionals for this study could also be justified by another earlier study of Kalyuga (2013), who revealed that learners' prior knowledge significantly affected learning effects. It was indicated that experienced site professionals, with more prior knowledge in construction site, would experience varied learning effects from VR-based training, because of the differed working memory and cognitive load caused by the multimedia learning defined by Kalyuga (2013). Several personal traits such as prior knowledge, age, and computer skills as identified in different studies (e.g., Lim and Morris, 2009; Kintu et al, 2016; Alk and Temizel, 2018) could cause the varied learning performance. Therefore, in order to minimise the effects of personal traits on trainees' learning performance, university students with a similar experience and knowledge level of construction activities were selected as experimental participants instead of construction professionals. Conducting the experimental studies engaging human participants for this study gained the approval from the University's Research Ethics approval beforehand. Before starting the safety training, each participant was asked to sign the consent form. A total of 52 students agreed to participate, and 50 of them participated with valid skin resistance data collected. That was because out of the 52 students initially recruited, two students had high ranges of bodily movement during safety training, causing their skin resistance measurements abnormally fluctuating. Therefore, these two participants' data recorded had to be abandoned. The 50 valid participants were divided evenly into the two training groups (i.e., traditional and VR-based training approaches). The sample size of this study was considered reasonable both statistically and practically. Similar sample sizes for immersive-based experimental studies can be found in Leder et al. (2018), Han et al. (2020b), and Nie et al. (2021), where the sample sizes ranged from 40 to 53.

3.4.Experimental procedure

The experimental procedure is illustrated in Figure 5, following the five steps described from Sections 3.4.1 to 3.4.5.

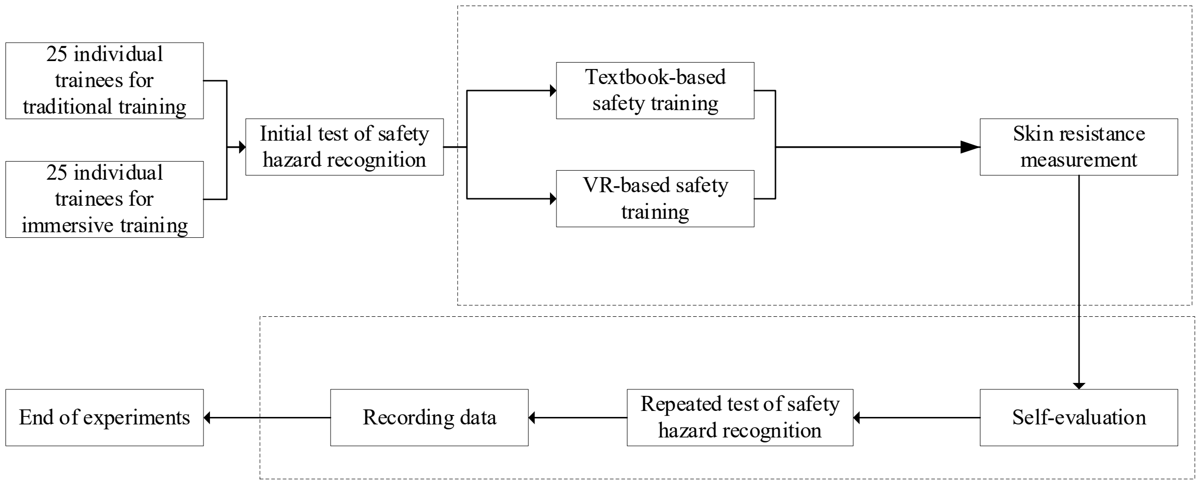


Figure 5. Description of the safety training process

A pilot study was conducted before formal experiments. Three pilot participants were recruited for the trails of the VR experimental system shown in Figure 3. Research assistants guided each participant in wearing VR hardware and the correct operation of avatars. The virtual site tasks completed by each participant was recorded, including the time consumed and the participant self-movement during the immersive site walkthrough. These recorded data during the pilot study provided feedback on the practicality of the VR system for the later formal experimental studies. Figure 6 demonstrates examples of the pilot study during participants' virtual site work.

Figure 6. Examples of immersive site activities during the pilot study

The pilot study showed the average time of completion for trainees was 5 minutes and 36 seconds. Researchers decided that 10 minutes were suitable as the time allowed for each trainee in completing the site tasks. It was also found that participants' large range of body movements would affect the data collection of skin resistance. It was hence decided that when conducting immersive site work (i.e., detecting and evaluating site safety hazards), participants' hand, which was wearing skin resistance sensor during the experiment, should be placed on the desk stably.

Following the pilot study of the whole immersive system trial and user feedback, the formal experimental workflow was standardised. Before each trainee started the formal immersive task, the laboratory staff would explain the experimental steps to ensure that the whole process was clear. It was also pre-planned by the researchers that any individual trainee's data would not be included in case of any interruptions occurring during the experiment or if the trainee's any personal reasons to discontinue the immersive task. The whole experiment process for each trainee consisted of the following five sequential steps: experimental preparation; tests of identifying safety hazards; measurements of physiological indicators during safety training; post-training test of safety hazard identification; post-experiment survey.

3.4.1. Experimental preparation

Two different safety training rooms were set corresponding to the two different training approaches. One room was prepared with the traditional safety training materials, and the other was set with VR-related immersive system. All other settings of the room, for instance, room environment, size, and safety training contents, were kept the same. Only one trainee would be allowed into the room at one time. Each trainee or participant would enter one of the two rooms depending on the education approach that had been priorly decided randomly by draws. Subsequently, each participant would be guided to sit quietly, with the left hand's index and middle fingers wearing the skin resistance sensors.

3.4.2. Tests of identifying safety hazards

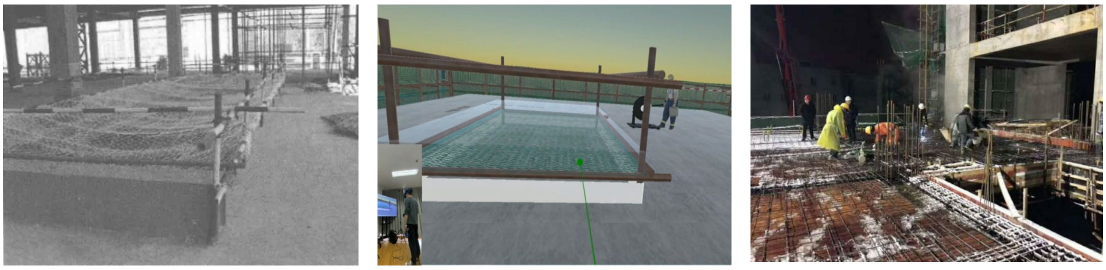
Before the formal safety training, each trainee was arranged with the pre-test of identifying hazards from given site scenarios. Laboratory staff recorded the time taken to complete searching hazards in 16 site photos and calculated the accuracy of hazard detection for each trainee. These site photos, part of which are shown in Figure 7, were collected from real construction sites. These photos underwent peer safety experts validation following the consistent procedure described in Han et al. (2020b). Basically, the scenes shown in selected photos were all related to typical safety hazards (e.g., lack of fall protection, improperly extended scaffolding) which did not conform to safety regulations and easily cause accidents. The hazards contained in these photos were validated and consistent with the follow-up construction safety training textbook and VR-based safety training.

Figure 7. Site photos for safety training in this study (note: only four out of the 16 photos are displayed in Figure 7 as examples)

A total of seven major hazard categories were included in both the VR-based and textbook safety training. The seven major categories included fall from height, collapse, electrocution, insufficient protective equipment, hit by heavy equipment, struck by objects, and hazards by lifting. These hazards were displayed in specific scenes or scenarios, such as: 1) no covering or protection around holes, causing the danger of fall at holes; 2) site employees not wearing hard hat; 3) obstacles existing within the turning radius zones of heavy equipment; 4) danger of electrocution for not wearing gloves to operate electricity distribution boxes; 5) non-existence of the other peer worker or supervisor when required; 6) electricity distribution box placed randomly, the box door not closed, or wires dropped at the floor; 7) broken safety net; 8) pile connection operation messed, or lack of easily seen accident evacuation channel; 9) workers not wearing seat belts; 10) no isolation net on the edge of the protection zones; 11) operators not wearing puncture-proof safety shoes with steel toe; 12) single point of lashing for tower crane lifting; 13) non-regulated maintenance edge; 14) materials not placed stably when working at height; 15) pedestrians passing under heavy objects during the lifting operation;

and 16) other hazards belonging to one of the seven major categories. Each of these 16 scenes was separately displayed for safety hazard tests. The same hazard scenes were adopted for both training groups.

Figure 8 displays an example of how the site photo was embedded in both the traditional and VR-based training.



a) Picture from safety textbook b) VR-based scenario c) Real site scene

Figure 8. An example of uncovered hole applied to both textbook and VR-based training

Each trainee was displayed with the site scenes. The trainee was asked to respond to questions regarding the existence of hazards in each site scene.

3.4.3. Measurements of physiological indicators during safety training

Each trainee, either in the traditional safety training or the VR-based group, was scheduled for safety training lasting about 10 minutes. During the training period, each individual was wearing the sensor and maintaining the two fingers of the left hand unmoved. Figure 9 shows an example of a trainee wearing sensors during safety training and the real-time display of skin resistance. At the beginning of each training, each trainee was guided by the researcher to ensure their skin resistance was stable as seen in Figure 9. Only after the flat and stable skin resistance data were confirmed for each trainee, the safety training process would start with continuing data recording of skin resistance. Therefore, the follow-up data collection and analyses of skin resistance recorded were based on the fact that each trainee started from the initially stable physiological status. The variation of skin resistance during the training would then reflect each individual trainee's emotional or mental status by eliminating the effects of each individual's initial status. Skin conductance level (SCL), is the tonic level of electrical conductivity of skin and reflects the general changes in autonomic arousal (Braithwaite et al., 2015). The overall degree of arousal (Malmo, 1959) of trainees as measured in Figure 13 in terms of lowest value, peak value, average value during the training process, and fluctuation value, reflects the principles of SCL. It was found from previous studies (e.g., Choi et al., 2011) that SCL was significantly correlated to individual's mental or physiological status.

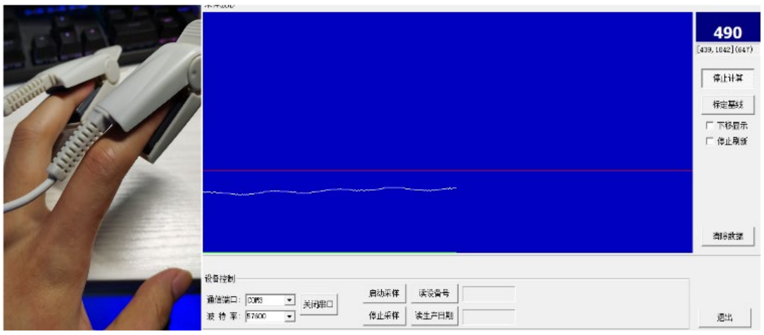


Figure 9. Display of skin resistance during the safety training

Trainees recruited in the group of traditional safety training read picture-based construction site safety textbooks. The training room was set with a sound-resistant screen to prevent any external noise. Laboratory staff equipped the trainee with skin resistance sensors and asked the trainee to leave the left hand unmoving on the table whilst self-studying the textbook. Laboratory staff then stood out of the view of the trainee until training was completed. Figure 10 displays examples of participants during the traditional safety training.

Figure 10. Trainees studying safety hazards in the textbook-based safety training

The other group of trainees receiving the VR-based training was guided to operate the immersive safety training platform shown in Figure 3 with the right hand. The training contents of safety hazards (e.g., site scenarios and hazard types) were kept consistent between the two groups. The VR-based immersive platform adopted the same site scenarios, including hazards from the textbook used in the traditional training group. The immersive training room was also set with consistent sound-resistant devices. Each trainee followed the instructions and guide within the immersive system to complete a virtual site tour, hazard learning, experiencing safety accidents virtually, and handling safety hazards. Figures 11 and 12 display the training devices and the room setup for each participant in the VR-based immersive safety training group.

Figure 11. VR headset for immersive construction safety training and other measurement devices

Figure 12. VR-based immersive safety training room

3.4.4. Post-training test of safety hazard identification

Following the safety training described in 3.4.3, the individual trainee would have a 5-minute break, and repeat the hazard recognition task in 3.4.2. The task performance of each trainee in terms of time of completion and accuracy rate was measured again to enable the follow-up evaluation of the effects of safety training.

3.4.5. Post-experiment survey

Each trainee was provided with a questionnaire upon the completion of their safety training and task. The nine indicators introduced in Section 3.1 is defined in Table 1, which is the post-training self-evaluation questionnaire to score the training system. Each indicator was scored by every trainee on a scale from 0 to 100. A higher score would indicate a more positive evaluation of the trainee towards the given indicator. The measurement scales from 0 to 100 were adapted from NASA-TLX principles (Hart, 1986), which evaluated individuals' mental status and effort in a multi-dimensional approach. In this scale system, measurement score for each indicator was equally divided into 20 ranges as seen in Table 1. The rationale for selecting a 100 point-based scale rather than the 1-5 Likert scale was also based on the fact that participants might hesitate to score between 3 and 4 and be more unlikely to choose 1 or 5 in a traditional Likert scale measurement. Further, the NSSA-TLX scale allows more varying scores among participants.

Table 1. Post-training self-evaluation of construction safety training

Self-evaluation measurement system		
Gender:	Group: VR group or Traditional training group	
Openness	A1: The training room was with sufficient space and not making me feel supressed.	0 Extremely low (Score from 0 to 100 to self-measure the given indicator) 100 Extremely high
Flexibility	A2: The safety training received was with flexible training methods and low restrictions.	0 Extremely low (Score from 0 to 100 to self-measure the given indicator) 100 Extremely high
Immersion	A3: The training received was immersive with little interruption from what had been occurring externally.	0 Extremely low (Score from 0 to 100 to self-measure the given indicator) 100 Extremely high
Ease of learning	A4: The training steps and instruction was easy to understand, with easy-to-follow guides.	0 Extremely low (Score from 0 to 100 to self-measure the given indicator) 100 Extremely high
Comfort	A5: The training process was comfortable both physically and mentally.	0 Extremely low (Score from 0 to 100 to self-measure the given indicator) 100 Extremely high
Interactive engageme-nt	A6: The training process was vivid and interactive by actively engaging personal senses.	0 Extremely low (Score from 0 to 100 to self-measure the given indicator) 100 Extremely high
Degree of fun	A7: Training process was pleasurable and interesting.	0 Extremely low (Score from 0 to 100 to self-measure the given indicator) 100 Extremely high

Proactive-ness	B1: The training approach made me more motivated and proactive in studying construction safety.	0 Extremely low (Score from 0 to 100 to self-measure the given indicator) 100 Extremely high
Degree of inspiration	B2: The training approach made me excited and inspired me to continue studying safety related issues.	0 Extremely low (Score from 0 to 100 to self-measure the given indicator) 100 Extremely high

4. Results

4.1. Data validation

Data through all trainees' participation were collected according to the two groups, namely immersive training and traditional safety training. Descriptive statistics are summarised for the two groups as shown in Tables 2 and 3.

Table 2. Descriptive statistics of physiological data between the two training groups (kΩ)

Training group	VR group (N=25)		Traditional training group (N=25)	
	Mean	Standard deviation	Mean	Standard deviation
Lowest value of individual skin resistance	259.52	96.78	318.80	84.26
Highest value of individual skin resistance	593.20	172.49	433.04	94.83
Average value of individual skin resistance	388.80	127.05	374.76	87.55
Variation of individual skin resistance	328.56	132.28	114.24	38.83

Table 3. Descriptive statistics of self-evaluation scores between the two training groups

Training group	VR group (N=25)		Traditional training group (N=25)	
	Mean	Standard deviation	Mean	Standard deviation
Openness	91.80	8.28	74.56	12.43
Flexibility	86.44	12.92	70.72	19.04
Immersion	88.68	8.75	65.20	16.10
Ease of learning	95.12	5.07	71.44	17.80
Comfort	93.84	6.47	75.12	15.82
Interactive engagement	90.84	7.78	64.88	20.73
Degree of fun	93.88	7.62	62.80	16.21

Data from both groups were found not meeting normal distribution following normal test described in Mishra et al. (2021). Mann–Whitney U test, as the non-parametric statistical analysis and accompanied with Kolmogorov-Smirnov statistic (KS Statistic) method, was adopted to test the level of significance for differences between the two groups. According to GraphPad (2022), Mann–Whitney U test ranks all values from low to hight with a *p* value to measure the discrepancy between mean ranks between two studied groups; KS test compares the cumulative distribution between two groups also using a *p* value; KS method is more sensitive to any differences in the two data distributions while Mann–Whitney U test is most sensitive to changes in the median. As the two methods are adopted in comparing two different data distributions or groups, this study adopts both tests to have more comprehensive comparisons. The four defined dimensions in Section 3.1 for comparative analysis were analysed, including self-evaluation of learning process, endpoint evaluation of learning outcome, physiological reaction, and learning performance. Non-parametric method such as Mann-Whitney test is more suitable for data that are skewed distributions or have a discrete or ordinal scale (Krzywinski and Altman, 2014). Following Krzywinski and Altman (2014), it can be assumed at 5% level of significance, and the null hypothesis that the two groups had consistent median values in the given dimension. A *p* value lower than 0.05 would decline the null hypothesis and indicate a significant difference between the two groups in terms of the given dimension shown in Tables 4-7. A lower *p* value would suggest a more significant difference between the two groups.

4.1.1. Analysis of physiological reaction during training

The statistical tests based on two different non-parametric methods for the skin resistance values between the two studied groups are summarised in Table 4.

Table 4. Level of significance in difference of skin resistance value between the two groups (N=50)

Variable	Mann–Whitney U test		KS Statistic	
	Z value	*p* value	Z value	*p* value
Skin resistance value (kΩ)	-5.850	0.000**	3.111	0.000**

Note: ** denotes *p* value lower than 0.01, indicating a significant difference between the two experimental groups.

The *p* values from both Mann–Whitney U test and KS Statistic methods indicate that different safety training approaches resulted in significant variation in terms of skin resistance between the two groups. A further evaluation could be conducted to analyse how the two different training approaches cause varied physiological reactions during safety training.

4.1.2. Self-evaluation of the training process

The two statistical methods applied to analyse trainees' evaluation of the training process also reveal significant differences between the two groups, as seen in Table 5. It can be found that the two studied groups differed significantly in each of the seven self-evaluation indicators related to the safety training process.

Table 5. Statistical analyses from self-evaluation of training process between the two studied groups

Variable	Mann–Whitney U test		KS Statistic	
	Z value	*p* value	Z Value	*p* value
Openness	-4.807	0.000**	2.404	0.000**
Flexibility	-3.259	0.001**	1.697	0.006**
Immersion	-5.096	0.000**	2.828	0.000**
Ease of learning	-5.248	0.000**	2.828	0.000**
Comfort	-4.456	0.000**	2.404	0.000**
Interactive engagement	-5.083	0.000**	2.546	0.000**
Degree of fun	-5.848	0.000**	3.111	0.000**

Note: ** denotes *p* value lower than 0.01, indicating a significant difference between the two experimental groups.

4.1.3. Evaluation of learning performance

For each trainee within the group of either immersive training or textbook-based training, the improvements in terms of time taken to complete and the accuracy rate of detecting site hazards were recorded or calculated by comparing the outcomes of the two tests introduced in Sections 3.4.2 and 3.4.4. The *p* values lower than 0.01 in Table 6 indicate significant differences regarding the improvements caused by the two different training approaches.

Table 6. Statistical analyses of learning performance between the two studied groups (N=50)

Variable	Mann–Whitney U test		KS Statistic	
	Z value	*p* value	Z Value	*p* value
Improvement in time of completion	-2.670	0.008**	1.697	0.006**
Improvement of hazard recognition accuracy	-5.524	0.000**	2.828	0.000**

4.1.4. Self-evaluation of learning outcome

The two indicators in light of trainees' evaluation on the training approach's impacts are statistically analysed in Table 7. The lower *p* values from the analyses of both indicators indicate the significant differences between the two training groups.

Table 7. Statistical analyses of learning outcome between the two studied groups (N=50)

Variable	Mann–Whitney U test		KS Statistic	
	Z value	*p* value	Z Value	*p* value
Proactiveness	-2.670	0.008**	1.697	0.006**
Degree of inspiration	-5.524	0.000**	2.828	0.000**

4.2. Further analyses of experimental data

The whole data sample was based on the 50 experimental participants (i.e., trainees), defined by the four different dimensions of measurements on the effectiveness of the allocated safety training approach. These dimensions included both subjective (e.g., self-evaluation of learning process and outcome) and objective measurements such as skin resistance, time of completion and hazard recognition accuracy.

4.2.1. Differences in trainees' physiological reactions caused by the training approach

Trainees' physiological reaction during safety training was measured by skin resistance in this study. Figure 13 shows the comparisons of skin resistance in terms of lowest value, peak value, average value during the training process, and fluctuation value. The peak value of the VR group was 593 kΩ, higher than that in the traditional training group based on textbook training. It is seen in Figure 13 that the two groups had a close average value during their training process, i.e., 389 kΩ compared to 375 kΩ. However, the fluctuation value, which is the difference between the peak and lowest values of skin resistance, indicates that VR group underwent significantly higher variations (i.e., 329 kΩ versus 114 kΩ) of physiological reactions during training.

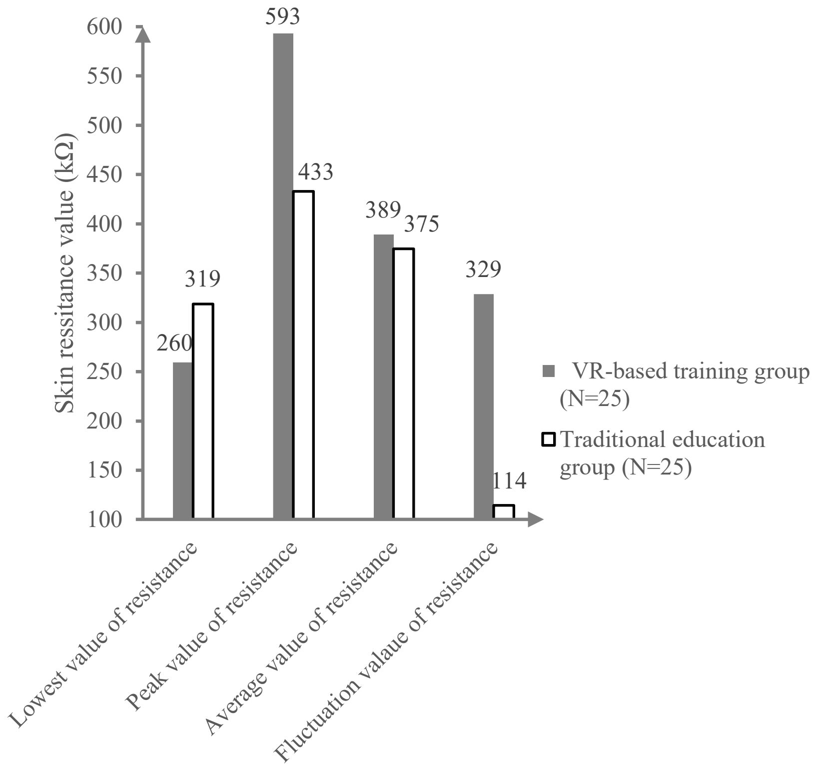


Figure 13. Comparison of skin resistance (kΩ) between the two training groups

A further analysis shown in Figure 14 found that the VR group had 23 individual trainees with a fluctuation value higher than 200 kΩ. In contrast, the traditional training group had only one trainee. It is inferred that a high fluctuation of skin resistance is a common phenomenon for VR-based trainees. When the body is in a state of emotional arousal, sweat secretion increases, skin conductivity rises, and skin resistance decreases (Khalfa et al., 2022; Vrana and Rollock, 2002). As counted in Figure 14, among the totally 22 individual trainees with the lowest resistance value below 200 kΩ, VR group contributed to 17 of them. It is hence indicated that VR-based training brings a higher degree of emotional experience during safety training. For example, during the VR-based immersive site tour, the trainee would experience falling from height as “punishment” if failing to identify the hazard for uncovered opening. The intense scenario changes bring strong emotional experiences to trainees in the immersive environment, making the trainees nervous or excited. The real-time collected physiological data showed the large change of skin resistance value during the time period when a trainee failed to detect safety hazards. Therefore, the newly developed VR system had created virtual scenarios that to some degree, represented the real site environment to spark the immersive experience for trainees.

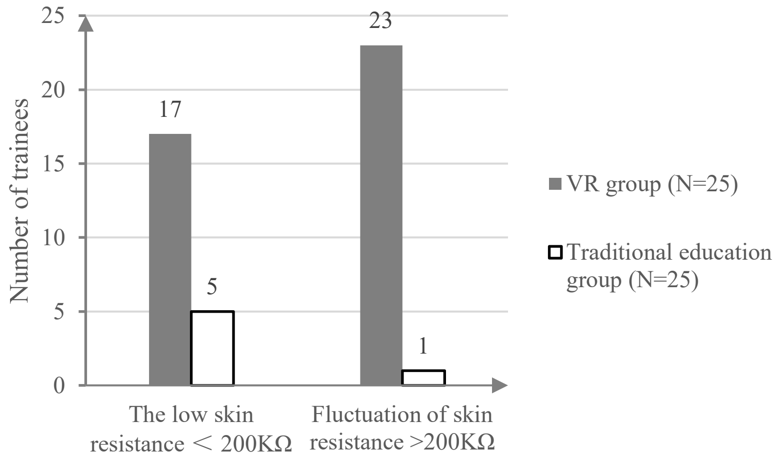


Figure 14. Numbers of trainees falling into the defined skin resistance ranges

In the virtual environment, trainees would be more likely to be excited by multi-sensory stimulations, resulting in higher physiological reactions in terms of skin resistance, which could be adopted as the measurement for emotional fluctuation, brain arousal, and alertness (Boucsein, 2012). The significant differences in skin resistance value variations between the two training approaches indicated the stimulating effects of VR-based training on individuals' sensory reactions. The close average values of skin resistance during the training process between the two groups, as shown in Figure 13, indicated that the VR-based training has maintained the overall emotional reaction of trainees at a normal range.

4.2.2. Comparisons of trainees' self-evaluation on the learning approach

Self-evaluation of the training received is another important measurement dimension of the training effectiveness through learners' reflections. Experimental participants from the two different training approaches are compared based on their self-evaluation scores towards the nine indicators defined in Table 1. Figure 15 compares the scores of each indicator between the two groups. It is seen that VR group scores significantly higher at all the indicators compared to their counterparts from the traditional training group. Figure 15, together with

Tables 5 and 7, indicate that the VR-based training results in more positive evaluations from trainees in terms of both the training process and the post-training impacts (i.e., motivating the continuous learning and the inspiration).

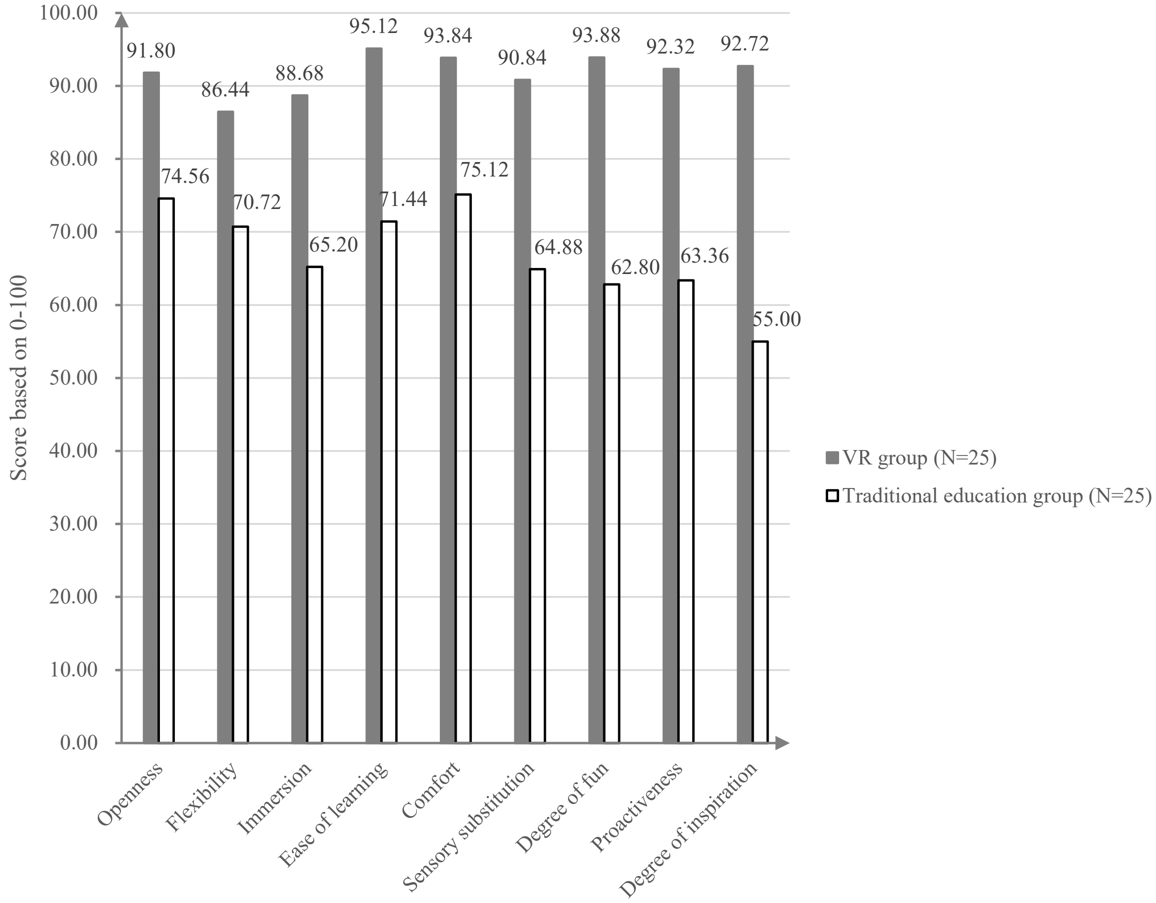


Figure 15. Trainees' self-reflection of the safety training process

Among the seven training process-related indicators, the highest differences between the two groups are found in the indicators of immersion, ease of learning, interactive engagement, and degree of fun. Trainees found the VR-based training with a significantly higher degree of fun, which could be related to the immersive experience and interactive engagement brought by the VR-driven platform. The immersive environment and multi-sensory engagement can more easily make the trainee concentrate on the learning tasks. In contrast, the traditional training needs learners to convert the 2D information from the textbook into real site safety scenarios. Learners or trainees in the traditional group tend to spend more effort in studying and memorising the text or static information from the textbook. Differing from the textbook-based training, learners in the VR-based training can experience more interactions with the dynamic and immersive site scenarios.

The two indicators related to the post-training outcome demonstrate even more significant differences between the two groups as seen in Figure 15. The highest difference comes from the degree of inspiration. The VR-based training significantly differs from the traditional safety training in terms of motivating trainees' relational thinking, which is highly connected to inspirational learning. The virtual environment provides an immersive site experience to trainees, engages multiple bodily sensing (e.g., visual and vocal), and enables relational thinking through human-immersion interactions. In the VR-based training approach, trainees could more easily capture the safety knowledge through virtual site exploration and interaction. Trainees could even further develop their own safety awareness with relational thinking towards other potential site safety hazards not covered in prior learnings. The traditional textbook learning would need trainees in a less active manner to link static images and texts into the real site scenarios. In comparison, VR-based safety training more actively drives learners to relate the virtual scenarios to real site safety hazards. Through this actively relational thinking, trainees would be more likely to make instant and proper decisions onsite when handling safety hazards.

Researchers counted the number of individual trainees from each group scoring over 80 out of 100 for each given indicator. Figure 16 shows that more than 80% of trainees from the VR group assigned the evaluation score over 80 for each of the nine indicators. This number from the traditional training group is significantly lower for each indicator. Figure 16 shows that trainees from the VR group held significantly higher positive perceptions in terms of the learning process and post-learning impacts from the training approach that they received.

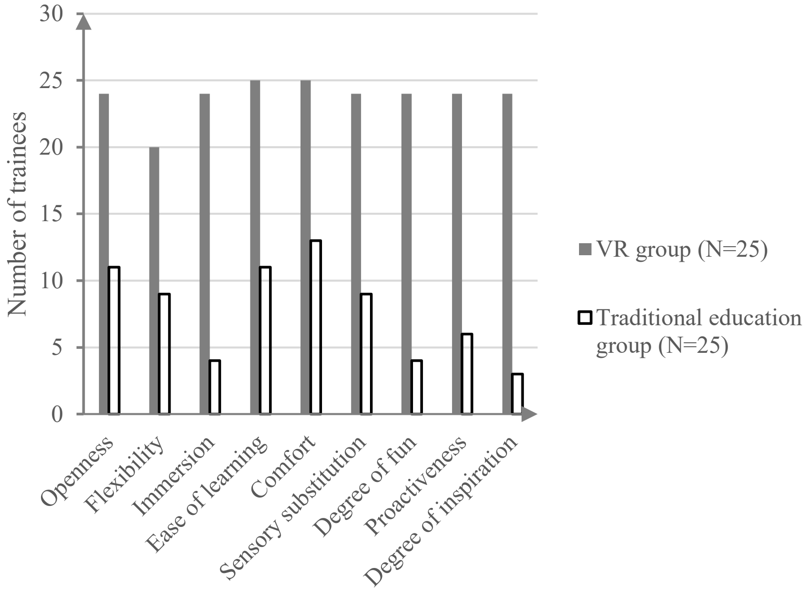


Figure 16. Counts on number of trainees scoring over 80 out of 100 for the nine indicators in the studied group

4.2.3. Comparisons of learning performance

The site scenarios selected for the task of safety hazard recognition all came from real-word construction projects. A total of the same 16 scenarios were tested for each trainee. For each trainee, the accuracy rate and time spent on detecting hazards from all the given scenarios before and after the training were compared for both groups, as illustrated in Figures 17 and 18. It is seen in Figure 17 that the VR-based training reduced the time spent on detecting hazards by 17.36 seconds, compared to the reduction by 7.72 seconds in the traditional training group. In terms of detection accuracy rate, the VR group, on average, had their hazard recognition performance improved by 22%. In contrast, the traditional group had not improved the accuracy rate, but with a minor reduction. Both indicators showed that VR-based training outperformed the traditional safety training by improving learning performance.

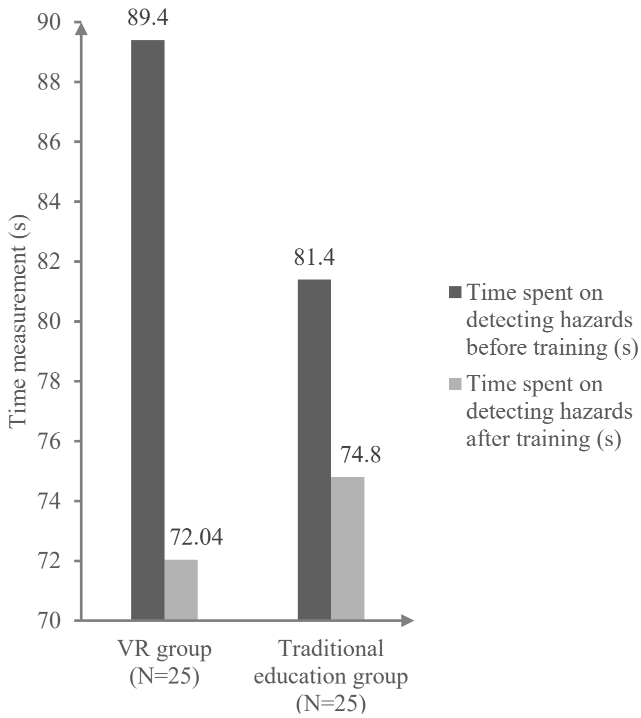


Figure 17. Comparisons of time spent to detect safety hazards before and after training

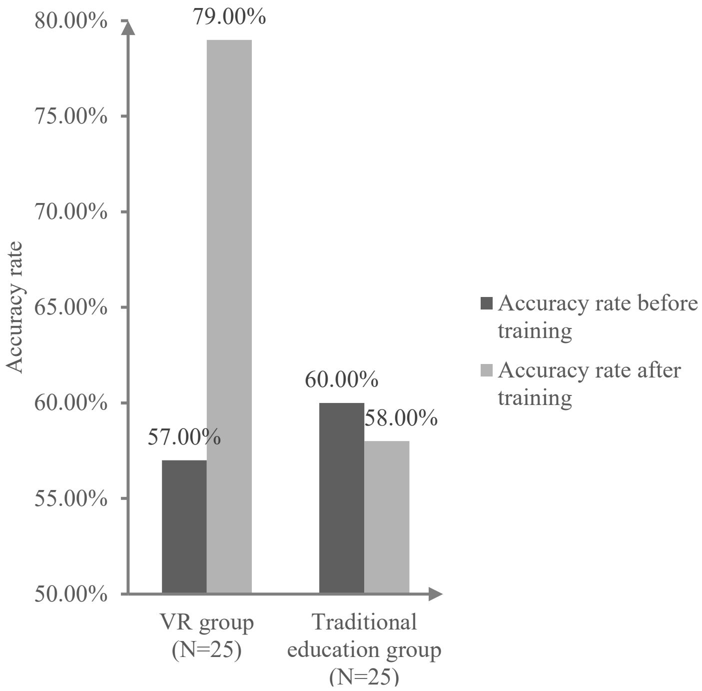


Figure 18. Changes in safety hazard recognition accuracy rates following training

Further data analysis showed that 92% of individuals in the VR group achieved their accuracy improvement by at least 10%. Instead, only 12% of individuals from the traditional training group achieved the same level of accuracy improvement. In terms of time spent on recognising hazards, individuals from the VR group also outperformed their peers from the traditional training group, as indicated in Figure 19.

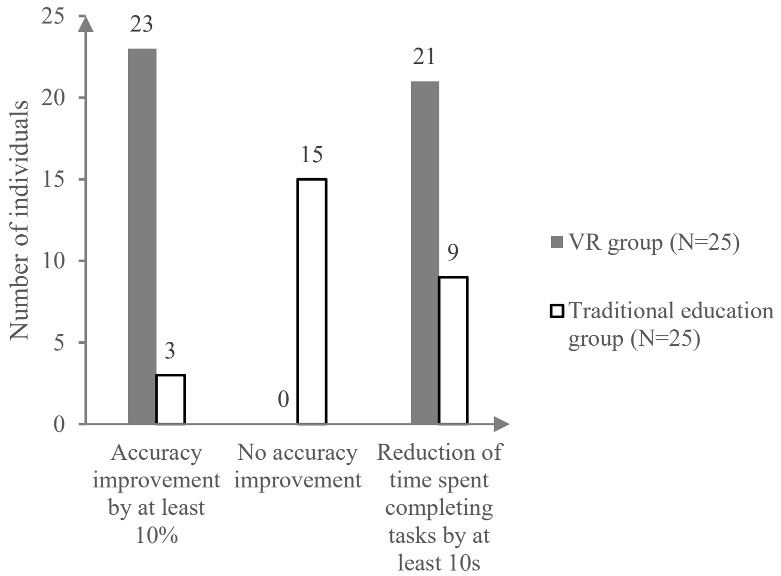


Figure 19. Counts on number of individuals on measured improvements before and after training from both groups

The number of individuals that achieved the two measured improvements in terms of accuracy and reduction of time spent completing hazard detection are compared between the two groups. Compared to 0% of VR group individuals who did not improve their accuracy in hazard detection, still 15% of trainees from the traditional training did not achieve any improvement. A total of 21 out of 25 individuals from the VR group were able to reduce the time spent on tasks by at least 10 seconds. This proportion was only 9 out of 25 in the traditional group.

4.2.4. Correlational analyses between measurement dimensions of training effectiveness

The training effectiveness could be affected by multiple factors such as learning environment and training approach. The differences identified between VR and tradition training of safety hazards can be further analysed by investigating the correlations between these pre-defined dimensions, for example, the relationship between physiological reaction and learning performance shown in Table 8, as well as the correlations between learning performance and self-evaluations as seen in Table 9. Following the guide from Bishara and Hittner (2012) on conducting correlation analyses for non-normally distributed data, the Spearman's correlations analyses were conducted as shown in Tables 8 and 9.

Table 8. Correlational analysis between physiological reaction and learning performance

Variable		Time improvement	Accuracy improvement
Skin resistance	Spearman's correlation	0.198	0.640**
	p	0.167	0.000
	N	50	50

** denotes *p* value lower than 0.01; *denotes *p* value lower than 0.05

Table 9. Correlational analysis between self-evaluation of learning process and learning performance

Varia-ble		Openness	Flexibility	Immersion	Ease of learning	Comfort	interactive engagement	Degree of fun	Proactive-ness	Degree of inspiration
Accu-racy improvement	Spearman's correlation	.609**	.430**	.689**	.587**	.487**	.666**	.774**	.607**	.736**
	p	0.000	0.002	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	N	50	50	50	50	50	50	50	50	50
Time improvement	Spearman's correlation	0.247	0.11	0.197	0.092	.300*	0.2	.294*	.332*	.399**
	p	0.084	0.449	0.171	0.525	0.034	0.163	0.038	0.018	0.004
	N	50	50	50	50	50	50	50	50	50

** denotes *p* value lower than 0.01; *denotes *p* value lower than 0.05

The correlational coefficient and corresponding *p* values in Tables 8 and 9 indicate that physiological reaction and self-evaluation had significant correlations with the accuracy improvement in detecting safety hazards, but not with time reduction in detecting hazards. VR-based training typically caused a more intense engagement of trainees measured by skin resistance, with more positive feedback towards the training, and hence resulting in better learning performance.

4.2.5. Further analysis

Traditional safety training mainly engages learners through reading and listening. Learners are largely engaged in a passive way by being fed with the information. If not further digested or processed by the individual trainee, the learning content or information could soon disappear or become ineffective in the knowledge storage of individuals. This ineffectiveness could be indicated by the lack of improvement in hazard recognition after the training in the traditional training group. The traditional safety training approach was largely based on 2-dimentional text and images, requiring trainees to further memorize and process the information. Different from the traditional training, VR-based immersive approach integrates active and passive learning manners, and enables trainees to experience hazards in the immersive environment. The virtual site tour provides a context in the safety hazard scenario. Interactive learning enables trainees' embodied cognitive processing of hazard information. Learners' multiple sensory participation in the immersive environment, such as experiencing accidents in VR, can more effectively store hazard-related knowledge through cognitive learning to form a more in-depth memory of safety hazards. As tested by the earlier study of Han et al. (2021), a lower cognitive load typically resulted in better task performance, such as hazard recognition. The reduced time to complete tasks, besides the accuracy improvement, also suggested the effectiveness of VR-based training approach.

5. Discussion

5.1. Learning environment in the VR-based safety training

Embodied cognition is based on the theory that cognition, thinking, memory, emotion and attitude are all shaped by the interaction between human body and the environment (Ye, 2015). Individuals' capturing and development of knowledge highly depends on the environment where the body is placed (Robbins and Aydede, 2009). VR-based safety training provides a new learning environment and experience. The post-experiment evaluation revealed that trainees from the VR group held significantly more positive views on the immersion. It was indicated that the embodied learning environment created by the VR-driven immersion enabled learners to have the direct feeling and emotional engagement in experiencing site hazards. This immersive experience can highly arouse different brain parts, including the thalamus for visual, auditory, and somatosensory engagement, cerebellum for regulating balance and body movement, as well as cerebral cortex. As a result, learners had a stronger immersive experience as if they were working on sites viewing the hazards.

The theory of situated cognition describes that the rich information contained in the environment helps cognitive processing (Wilson, 2002; Olson and Olson, 2003; Chrisly, 2004), and enhances learning performance in understanding concepts and seeking solutions (Glaser, 2001; Kirsh, 2009). As demonstrated in this comparative experimental research of safety training, the environment is created by the different information channels (i.e., traditional textbook or the VR-based immersion). In the traditional safety training, information is mainly in the form of 2D text, static images, or videos. In the VR environment, such as the VR platform developed by researchers in this study, information is presented in the immersive 3D through the virtual site tour. Individual trainees have their virtual site walkthrough, searching site hazards, handling the hazard, experiencing the safety accidents, and also studying safety operational regulations. For those with limited education background, such as workforce, and those with little site experience, the virtual site information presented with multiple sensory engagements (e.g., visual, virtual site noises) can be more effective than traditional 2D based information during safety training. The VR environment can reduce the cognitive load needed for processing the information, decrease the learning difficulty, and hence improve the learning outcomes. The post-experiment survey also showed that trainees from the VR group generally perceived the ease of learning safety hazards. As indicated by Sternberg et al. (2012), learners tend to encode the content of learning and the environment, and store it in their long-term memory. The environment features or contexts will serve as effective clues for information retrieval in future recalls (Sternberg et al., 2012). This theory can be verified in the VR-based safety training, where learners significantly improved their accuracy and reduced time spent for completing the hazard detection tasks after the training.

The multi-sensory engagement, as forementioned, reduces the distraction as trainees may experience during the learning process. For example, noise occurring during training can affect learners' allocation of attention resource, and further disturbing the information processing for knowledge storage. Sudden or unexpected noise could inevitably happen in the traditional safety training environment. In the VR environment, learners wearing headsets in this study were listening to the site background sound during virtual site tour to help them better immersed. Learners were more engaged both visually and vocally on searching safety hazards, and hence less likely to be affected by other non-relevant distractions in the training room.

5.2.Embodied cognition enhancing the learning process

Human beings' cognitive learning process can be divided into sensory, information processing, and reaction stages. The information processing stage involves memorizing and storing the knowledge. Safety training aims to form the proper safety cognition and to further develop appropriate safety behaviors of trainees. The traditional textbook-based training is limited to two-dimensional text or image information. Trainees are likely to have a single-sensory engagement in viewing and processing information. Following the principles of psychology and human performance described by Wickens et al. (2021), Figure 20 models the process of knowledge storage and reaction within the traditional textbook-based learning environment.

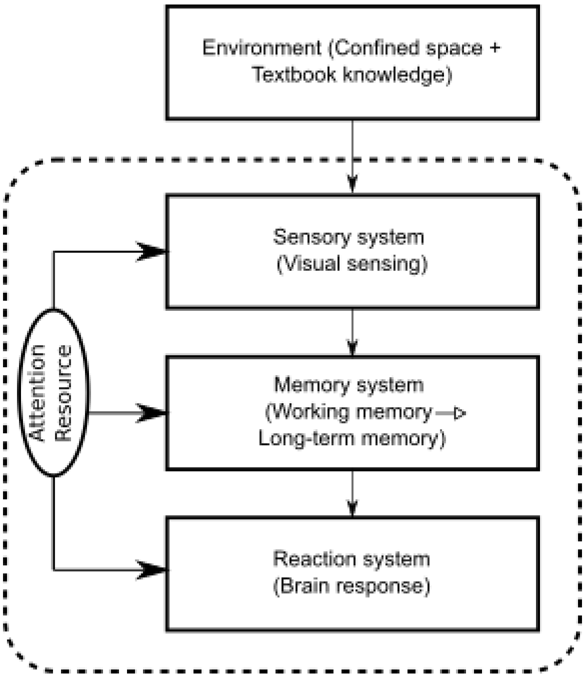


Figure 20. Mechanism of traditional learning and information processing

In this study, researchers proposed that VR-based training could embed embodied cognition to enhance interactive learning in the immersive environment. In the immersive site tour, trainees do not only observe hazard-related information, but also the surrounding context in a more holistic scenario. For example, the building's different elements, site equipment, and layout are all context information where the hazards could be. VR-based immersion can provide the whole picture, rather than only presenting the hazard in an isolated manner as in traditional textbook training. Post-experiment reflection from participants indicated that from the VR-based site tours that they would more frequently pay attention on higher locations on site after experiencing the virtual falls from height due to ignorance of hazard. Trainees stated that they would hence more likely to search the relevant hazards such as fall in the given site scenario.

The subjective measurement through post-experiment survey complemented the task performance to measure the training effectiveness. Trainees from the VR group scored significantly higher than their peers from the traditional training group in evaluating the training process and the longer-term impacts. It was inferred that VR-based training provided more inspiration and motivation for participants during safety training. VR-based training does not really change the learning process, as shown in Figure 20 for traditional training. However, VR provides richer information and context to stimulate trainees' sensing, such as the whole virtual site scenario to engage trainees. The virtual environment of construction sites hosts all information, including safety hazards. As illustrated in Figure 21, during the interactive training process, an individual trainee and the immersive environment work as the information source to each other. This interactive process enabled trainees' multi-sensory engagement i.e., the embodied cognition in the training process.

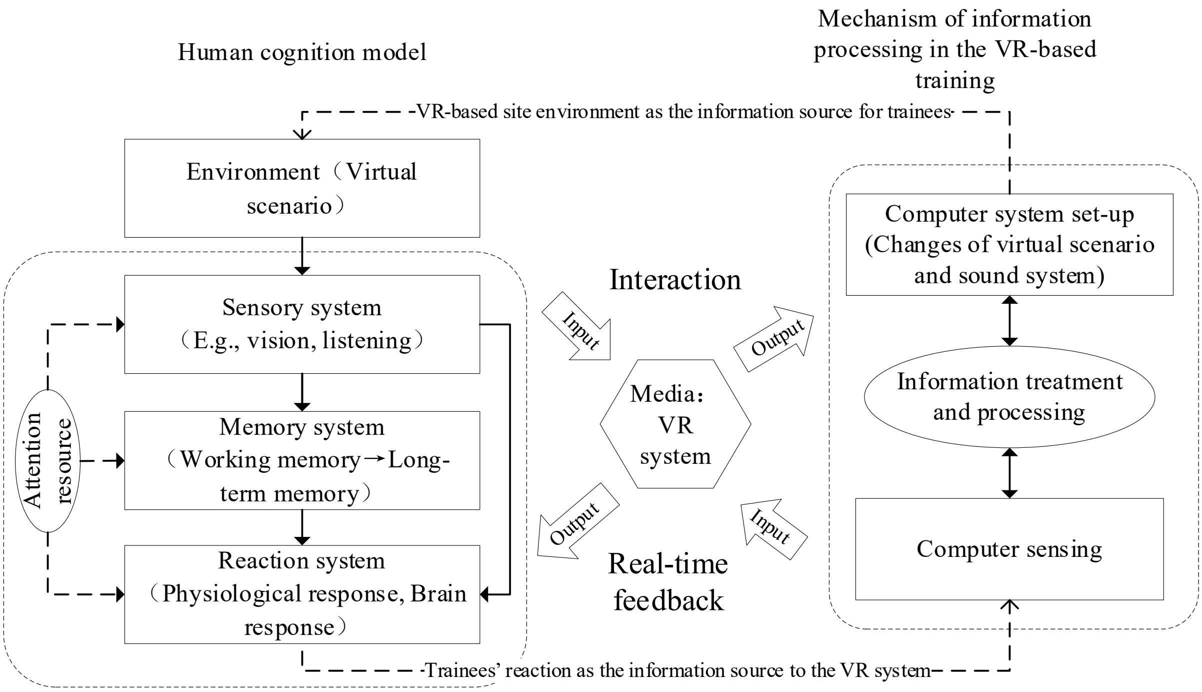


Figure 21. Embodied cognition model of learner engagement in the VR-driven safety training system

Figure 21 demonstrates a cognition model via a virtual environment. It is constructed based on the human-computer interaction model (Guo, 2020). Individuals develop cognition during their interaction with the VR system. The information provided by the VR scene through the visual and auditory channels is firstly perceived by an individual, and stored in the memory system. The individual then makes decision in responding to the information received. The VR system presets its scenarios with sound system. Similar to the human cognitive process, after information processing, the VR system reacts to the individual with updated scenes and sound effects. Through this bespoke process of interaction, the individual and the VR system continuously exchange information and feedback. This bodily engagement could cause physiological and emotional arousal as indicated in Figure 13, and further influencing the cognitive outcomes. The site environment is the carrier of safety knowledge related to hazards, and presents the safety knowledge to trainees in a visualized and dynamic manner. On the other hand, the individual trainee's behaviour during the virtual site tour also feeds back to the VR system. For instance, ignoring safety hazards or improper reaction to identified site hazards would cause a sudden (virtual) fall of the trainee. Therefore, the trainee and the VR-based site environment are in a dynamic interaction, and continue feeding back to each other. This interaction and real-time feedback between the trainee and the environment are not available in the traditional safety training. VR provides succinct but vivid scenarios which enable a longer term memory to be established (Hu, 2021). VR-based construction safety training enhances building the safety knowledge through specific scenes (Liang and Huang, 2008). As a result, the learning performance and trainee evaluation are improved. The embodied cognition could also enhance the inspiration and motivation for continuous learning.

Knowledge acquiring, emotional experience, and behavioural reaction form the process of embodied cognition (Ye, 2015). Cognitive activities are inseparable from body participation, while physiological changes and emotional responses are the individual's reactions to the stimulus events (Ye et al., 2021). Both positive and negative emotions during the cognitive process will strengthen the memory coding for the future retrieving of the stimulus (Baddeley et al., 2018). By measuring physiological data such as skin electrokinetics and heart rate changes, Christianson and Nilsson (1984) found that there would be voluntary emotional awakening during the memorizing process. Similarly, the skin resistance variation was identified after safety training. This variation was more significant in the VR training group than the traditional training group. The objective data captured from skin resistance could also be validated by the subjective measurements through post-training questionnaire survey, which also indicated that trainees had stronger emotional arousal in the VR-based training. Emotional arousal could provide a facilitating effect on memory encoding of individuals, and create more reflexive attention and thinking , as indicated by Heuer and Reisberg (1990).

Safety in construction work is highly related to preventive awareness and knowledge in a dynamic and risky site environment. Safety training might be downplayed as it is often considered with little contribution to the income generation of construction workforce. Workers typically only pay attention to their site activities to complete tasks that directly matter to their income, but with limited attention to safety knowledge or safety training. The traditional safety training tends to be more towards passive learning and lacks the engagement of individuals. The training effectiveness is not uncommonly in question. Instead, the emotional arousal stimulated in the VR system, such as the virtual experience of fall from height, collapse of scaffolding, and struck-by, etc., increases the interaction between the trainee and the VR system. The immersive and multi-sensory engagement can transform the traditional passive learning into a more active learning mode.

Safety accidents often cause serious injuries and even fatalities. However, trainees in a third-person experience by reading texts, listening, or watching videos in the traditional safety training may not be fully engaged in realising the seriousness of accidents and hazards. The VR system allows learners to gain specific and profound experiences through engaging bodily senses. At the same time, the first-person learning perspective provided by the VR system strengthens the emotional participation of individuals, and enhances the sense of substitution in the virtual environment (Chen, 2020). This first-person perspective of learners during safety training also evaluates the scenario setup, interaction, and immersion of the designed VR system. The empathy and emotional arousal in experiencing site accidents caused by hazards integrate trainees' feeling, awareness of hazards, understanding, and reaction. The individual trainee becomes part of the virtual site in the active learning, rather than being a bystander as in the traditional training. The first-person experience is strengthened by virtually walking through the site and by also observing other non-hazard-related information in a holistic picture. Hence, the trainee builds his/her own safety knowledge through the virtual walkthrough in the first-person perspective.

This first-person experience is enabled by the interaction between the learner and the VR system, as well as the immersive environment created by the VR technology. VR, as the technical media, bridges the learner and the actual world (e.g., construction site hazards in this study). The physiological reaction together with emotional arousal were strengthened by this first-person experience, as indicated by the post-experiment questionnaire survey and the skin resistance analyses. The storyline or scenarios of safety hazards embedded in the virtual site can be updated within the VR system to reflect the real world site hazards and training needs.

6. Conclusion

Although immersive technologies involving virtual reality (VR) have been applied in construction safety training as an alternative to the traditional safety training, there has been a lack of empirical data to test the effectiveness of VR-based training mode versus the traditional approach. To address this need, this study adopted the self-developed VR-based construction safety training system to compare the effectiveness between the traditional safety training and the VR-based approach. Both objective and subjective data were collected involving the training process and outcome. Objective data included the skin resistance measurements of each individual during the training, and the task performance as outcomes. The subjective measurements were based on the post-training questionnaire survey collecting individuals' evaluation of the training process and post-training impacts. Both the subjective and objective data collected based on the training process and task performance revealed the consistent findings that VR-based training approach outperformed the traditional safety training in terms of trainees' interactive engagement and learning outcomes.

The differences between the two safety training approaches can be summarised in the following aspects:

a) VR-based training involving embodied cognition enables trainees' physiological reaction and emotional engagement. Compared to the traditional training, VR-based training caused a higher fluctuation of skin resistance, which reflects a higher level of sympathy and emotional arousal;
b) Learners gain a better experience through virtual and immersive training. The post-experiment questionnaire survey revealed that VR group learners had a significantly more positive experience towards the training process (e.g., degree of fun). Learners from the VR group also held more positive views regarding the inspiration and motivation of continuing safety training following the training;
c) The bodily engagement through interactive learning in the immersive environment can enhance the learning performance measured by accuracy and time spent on hazard detection. VR-based training could decrease the cognitive load spent on learning safety hazards through multi-sensory engagement and could further enhance the longer-term memory of safety hazards.

Following the theory of embodied cognition, these findings were achieved:

1) By providing the immersive environment, interactive mode, and the first-person experience, VR-based system could meet the training needs in construction safety with enhanced learning experience and training outcomes. This enhancement could be explained by the embodied cognition theories. Basically, trainees or learners could obtain the nearly-real-world perception from the immersive environment, with stronger emotional arousal

through interaction with the VR system. Further, the trainees could form the embodied cognition with the first-person experience in the virtual site, and transform it into longer-term memory. Finally, safety awareness and knowledge can be improved through VR-based training.

2) Differing from the traditional training, VR-based training motivates individual trainees through multiple bodily sensory engagements. Trainees can better allocate their attention resources with reduced distraction and lowered cognitive load. This multi-sensory engagement strengthens both the physical and mental participation, and bridges the trainee and the virtual environment. This information processing and memorizing of safety hazard related knowledge, through embodied cognition, can further motivate trainees' reflective thinking and active learning. Specifically, trainees have enhanced experience during the training process through immersion, fun, ease of learning, first-person experience, and inspiration, all of which boost the learning performance.

The current study has several limitations. Firstly, the potentially negative emotional reactions during VR-based training, such as nervousness and uncertainty of trainees, were not measured during the study. Therefore, it remains unknown how these negative reactions could affect cognitive learning and performance. The future study can consider extending the measurement dimensions in the post-experiment evaluation by including these negative reactions. Secondly, the post-training test of safety hazard recognition was conducted on the same day of the training. It only measured the short-term learning performance of trainees following safety training. The longer-term learning performance of hazard recognition is yet to be tested by comparing the VR-based and the traditional safety training. Future research could be extended to test the longer-term performance of trainees, e.g., one week or one month after the safety training. More research is needed to evaluate how long and how often VR-based training could optimally enhance individuals' learning performance.

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