Advanced Engineering Informatics 50 (2021) 101431

Contents lists available at ScienceDirect

Advanced Engineering Informatics

journal homepage: www.elsevier.com/locate/aei

Effectiveness of VR-based training on improving construction workers' knowledge, skills, and safety behavior in robotic teleoperation

Pooya Adami [a], Patrick B. Rodrigues [a], Peter J. Woods [b], Burcin Becerik-Gerber [a,*], Lucio Soibelman [a], Yasemin Copur-Gencturk [b], Gale Lucas [c]

[a] Department of Civil and Environmental Engineering, University of Southern California, Los Angeles, CA, USA
[b] Rossier School of Education, University of Southern California, Los Angeles, CA, USA
[c] USC Institute for Creative Technologies, University of Southern California, Los Angeles, CA, USA

ARTICLE INFO

Keywords:
Construction robotics
VR-based training
Human-robot interaction
Safety behavior
Operational skills
Knowledge acquisition

ABSTRACT

The emergence of construction robotics and automation has produced an urgent and vast need for construction workers to reskill and upskill for the future of work. Virtual Reality (VR)-based training has been considered and investigated as a safe and cost-effective training method that allows workers to be exposed to hazardous tasks with negligible actual safety risks in comparison to existing training methods (hands-on, lecture-based, apprenticeship training). This paper aims to investigate the impact of VR-based training on construction workers' knowledge acquisition, operational skills, and safety behavior during robotic teleoperation compared to the traditional in-person training method. Fifty construction workers were randomly assigned to complete either VR-based or in-person training for operating a demolition robot. We used quantitative and qualitative data analyses to answer our research questions. Our results indicate that VR-based training was associated with a significant increase in knowledge, operational skills, and safety behavior compared to in-person training. Our findings suggest that VR-based training not only provides a viable and effective option for future training programs but a valuable option for construction robotics safety and skill training.

1. Introduction

Although the construction industry is one of the largest industries globally, accounting for 6% of the world's GDP [1], it also faces significant challenges such as safety issues, skilled labor shortages, and low productivity rates. In fact, the construction industry has the highest number of fatal and non-fatal injuries across all industries. According to the U.S. Bureau of Labor Statistics, the U.S. construction industry accounted for 1,061 occupational fatalities in 2019, a number higher than any other industry [2], and the Center for Construction Training and Research reported that the construction industry also has a significantly higher rate of non-fatal injuries (29.2% higher) than any other industry [3]. Added to that, the Occupational Safety and Health Administration (OSHA) estimates that half of workplace injuries go unreported each year [4]. Besides these safety concerns, the industry is also hindered by severe worker shortages, especially skilled workers, with about 266,000 jobs being left unfilled across the U.S. in February 2021, as reported by The U.S. Bureau of Labor Statistics [5]. In terms of labor productivity growth, the construction industry has experienced lower productivity growth as compared to manufacturing and the total economy. In the period from 1995 to 2014, labor productivity in construction grew 1% annually while the productivity in the total economy grew 2.7% annually, and the productivity in manufacturing grew 3.6% annually, on average [6].

Automation and robotics are frequently presented as an alternative to alleviate some of the safety concerns, mitigate labor shortages, and improve productivity rates in the construction industry. In the past decade, it has been observed that the construction industry is experiencing a significant increase in the number of robots deployed on-site [7]. In addition, current reports indicate that more than 7000 new construction robots will be introduced to construction sites by 2025 [8] and that 46% of construction tasks have the potential to be automated [9]. While automation and robotics can increase safety on construction sites by removing workers from hazardous environments, interacting with new technologies can also create new safety concerns [10]. Therefore, it is important to train construction workers either in new

* Corresponding author.
E-mail address: becerik@usc.edu (B. Becerik-Gerber).

https://doi.org/10.1016/j.aei.2021.101431
Received 11 May 2021; Received in revised form 20 August 2021; Accepted 27 September 2021
Available online 7 October 2021

skills directly related to their current roles (upskill) or in new skills necessary for different roles (reskill) to interact with and control these new technologies safely and effectively. The McKinsey Global Institute presents upskilling and reskilling the workforce to deal with new technologies, automation, and digitization to increase productivity in construction [6] and prepare these workers and organizations for the future of work [9]. Over time, various strategies for training construction workers on the use of new technologies have been proposed and employed. These strategies vary from passive strategies (including lectures, pamphlets, presentations, and videos) to active strategies for training (computer-based or learner-centered instruction, apprenticeship models, and hands-on demonstrations). Existing research shows that both strategies have been associated with improved worker behavioral performance in safety and health and that more engaging training strategies are associated with increased knowledge acquisition and reductions in reported accidents and injuries [11].

Despite these benefits, not all construction tasks are feasible to be taught using more engaging training strategies due to a variety of technical, economical, safety, and ethical constraints. Construction sites are usually characterized by dynamic, unconstrained, and hazardous environments, making simulating many real-world scenarios during training complicated. First, it may be the case that more complex tasks that use specialized equipment may impose unjustifiable risks to the safety of the trainees and, for that, the trainees may not have a chance to experiment with many of the most complex situations likely to occur on-site. Second, the costs associated with acquiring the necessary equipment and materials for the training may be too high. Finally, in case the training is to be held on-site, the disturbances it creates to the job site may not be justified.

To address these concerns, Virtual Reality (VR)-based training is proposed as a method to provide construction workers with in-person training experiences in hazardous situations without imposing actual safety risks. In fact, VR-based training in construction has found applications in many areas, including construction safety [12–15], ergonomic behavior [16,17], operating construction equipment [18–21], and performing construction tasks [22,23]. However, limited research exists on whether VR-based training can indeed be used to train construction workers effectively to gain the necessary knowledge, skills, and safety behavior in robotics operations. This limitation partly exists because developing effective methods for training workers to learn how to engage with robotics in a VR environment is highly complicated. From the VR developer perspective, the accurate simulation of robots with high numbers of degrees of freedom, high levels of autonomy, and complex control mechanisms, as well as the complex interactions among various agents (e.g., humans, machines, robots, weather) that take place in a construction site are time- and resource-intensive tasks. When not properly performed, it may provide an incomplete training experience to the trainees. In addition, it is challenging to evaluate skill transfer from VR-based training to real-world settings [24]. From the trainee perspective, the operation of construction technology (e.g., heavy construction equipment, teleoperated robot) may be considered cognitively taxing, especially in aspects related to mapping control actions to technology functions [25]. Hence, a VR-based training needs to be equipped with an appropriate mental model to be effective. Finally, developing effective training is challenging considering the unique aspects of construction workers' demographics with potentially low English proficiency and low literacy. Evia [26] has confirmed that general translation of learning material is a limited approach in training Hispanic construction workers and proved that including more participatory design, emphasizing audiovisual components, and oral evaluations are better approaches for the ethnic minority (e.g., Hispanic) audiences. The U.S. construction industry has the highest percentage of Hispanic/Latino workers compared to other industries (30%) [27], who may be solely or mostly Spanish speaking (62%) [28] and are reported to have a lower education level (93% of White construction workers have a high school diploma compared to only 77% of Hispanic/Latino construction workers) [29].

In response, in this study, we investigate the impact of VR-based training on knowledge acquisition, operational skills, and safety behavior while working with the robot compared to a more traditional, comparable in-person pedagogical model and answer the following research questions.

1. How does VR-based training impact *knowledge acquisition* for construction workers compared to the traditional training method?
2. How does VR-based training impact construction workers' *safety behavior*, compared to the traditional training method?
3. How does VR-based training impact construction workers' *operational skills*, compared to the traditional training method?

Although several studies in the construction industry have investigated the effectiveness of VR-based training as compared to more traditional training modalities in terms of skills and knowledge acquisition [13–15], performance [30–33], and mental workload levels [34], most of the studies that focused on heavy construction equipment training have not included the actual equipment during the validation of the training effectiveness due to constraints related to costs and safety. In one of the few training studies in which simulated and real heavy construction equipment are compared, So et al. [35] point out that studies on skill transfer from VR to real equipment in construction are rare. In the present study, construction workers were trained on the teleoperation of a demolition robot, and the validation of the effectiveness of two training modalities (VR vs. in-person) was completed using the actual robot in a real setting. In most of the existing studies that included construction equipment such as cranes and excavators, for example, only experts controlled the actual equipment [36,37] while trainees controlled only simulated equipment [18,21,25,38]. Also, in the studies that involved a follow-up assessment using the actual equipment after VR-based training, only less dangerous and less complex equipment, in terms of their sizes/weights and control mechanisms, respectively, were used, as is the case with drones [34]. It is important to test the effectiveness of training relative to skill transfer with real equipment and robots because, due to the limitations of any simulation in terms of functionality and fidelity, some level of re-learning or new learning can be observed in the real setting after VR-based training [24]. Another difference in the approach used in this study relative to existing studies is the dissimilarities between training on traditional construction tasks (e.g., masonry construction, wall assembly) and robotics training. As robot implementation in the selected task fundamentally alters the way the task is performed and, by doing so, introduces new safety concerns to the task, proper consideration of these aspects must be considered during robotics training, which is shown in some of the training modules in the proposed framework.

We begin this paper with a literature review of existing studies into VR-based training from a wide range of educational contexts and vocational training literature. Next, we present the methodology of the research, including the VR-training environment development and the experimental design. We then present our research findings using newly developed VR-based training modules for a demolition robot with construction workers. Next, we discuss our findings, and finally, conclusions are presented.

2. Literature review

2.1. Knowledge acquisition

Since the 1990s, education researchers have posited the use of VR as a tool in education, recognizing its potential within both formal and informal classrooms [39]. In the ensuing years, multiple studies and theoretical works have tested and advocated for the value of engaging VR in the learning process [40]. Broadly speaking, these studies have routinely found that the use of VR-based education models results in higher or equitable levels of knowledge acquisition [41–45], retention [46–49], and transfer between contexts [45,50–53] when compared to more traditional approaches to learning (such as lecture, text, and digital media-based pedagogies).

Although these studies advocate for the potential of VR in learning, the effectiveness of VR in learning often relies on the specifics of that implementation and the program itself. As both Wikens [39] and Chavez and Bayona [40] contend, the design of programs largely determines whether or not specific technologies result in effective learning experiences. Additionally, Pantelidis [54] argues that educators and designers should not consider VR an all-encompassing tool in education but instead use VR intentionally in specific scenarios where the affordances of VR can improve learning outcomes. In other words, VR holds the potential to improve education practices but only if the context lends itself to this tool. For example, VR lends itself to learning processes and outcomes that rely heavily on visualization or visual information, while learning through auditory information may occur more effectively through other pedagogical modes [55–57]. Additionally, Jensen & Konradsen [58] have argued that many of the VR-based training/education studies do not provide the necessary rigor to make generalizable claims. However, when designers intentionally and purposefully construct those tools with these concerns in mind, VR represents a potentially powerful tool in the process of learning.

If VR can broadly provide a valuable tool in education, it follows that VR holds the potential to provide a valuable tool in educating construction workers. For that, in the past two decades, the use of VR-based training for educating construction workers has drawn much attention from construction researchers, especially in aspects related to hazard identification and safety in construction sites [12,32,59], with a more limited number of studies explicitly focusing on vocational training and machine operation training [19,33]. However, construction researchers have just recently started investigating the application of VR-based training in construction robotics, with some prototypes proposed but no validation [60,61].

The existing body of research into VR-based vocational education within the construction industry largely positions VR as a valuable tool [62] and, across existing studies, researchers have found that the use of VR over traditional pedagogical methods (i.e., lectures, text-based education, or 2D visual guides) has led to higher knowledge retention and application and a better ability to recognize hazards that appear in real-world job sites [13,63,64]. Delving further into these existing studies, the improved performance within VR-based safety training within construction contexts occurs for two main reasons, both of which align with Pantelidis' [54] guidelines for when VR should be used as an education tool. The first reason comes from the fact that interacting with construction equipment on job sites would often prove dangerous for trainees. Therefore, VR simulations provide a tool for workers to acquire “hands-on experience” without putting themselves at risk if they “fail” at training tasks [57,65,66]. Additionally, the very nature of a simulation allows for the intentional design of learning environments towards a specific end, representing a distinct advantage over real-world experiences. Schank [67], for instance, argues that designers can create simulations that align with research into cognitive development, thus ensuring the acquisition of knowledge to a higher degree. Eiris et al. [63] also recognize that VR can make normally invisible hazards (such as electricity) visible, situating VR as a robust learning context beyond real-world experience. Second, VR-based training methods also increase construction workers' concentration and engagement because they are involved in interactive experiences beyond the usual process of passively digesting information through audio, text, or images [13]. This does not imply that VR should replace teachers/trainers or learning materials (e.g., textbooks). Instead, multiple studies have found that VR-based training works best in the context of a more traditional teacher/student relationship [68,69].

Despite this increased use of VR-based technologies to train construction workers over the past two decades, most of the existing training programs were not designed based on adult learning theories. For the case of equipment simulators, specifically, Dunston et al. [24] present that most of the existing studies emphasize the technical aspects of the prototypes with less emphasis on learning and skill transfer. In many cases, it is also common that the training environments and modules do not allow the trainees to adapt their knowledge and skills in different scenarios, something that is critical to tasks that involve construction robots and that have detrimental impacts on performance and skill transfer when using the actual equipment after training. Tichon [70] argues that skill acquisition and performance depend not only on the design of the simulation but also on the evaluation of the training objectives relative to the required behavior in the real world, which can provide critical feedback that can improve the training program.

In this study, we grounded our approach in the adult learning theory (andragogy) [71]. As, this theory holds that adult learners are self-directed and independent, with a wealth of experience to draw upon when learning, a greater interest in problem-solving, and the need to immediately see the relevance of what they learn to the task at hand [72,73]. This study explores whether simulation activities that target key concepts and skills by leveraging the benefits of adult learning theory (andragogy) improve workers' knowledge and skill during VR-based training.

2.2. Safety behavior & operational skills

VR has been successfully implemented in several different vocational training initiatives with positive results across different industries [74–76], such as manufacturing [77–79], aviation [80], robotic surgery [81,82], and mining [83]. Additionally, Jou & Wang [84] found that VR provides an effective tool regarding skills training with manufacturing machinery. For construction applications, most of the existing studies have focused on hazard identification and safety training [12–15,32,85,86], with a more limited number of studies in areas such as ergonomic behavior training [16,17,87], construction equipment operation training [18–21,24,38,88–90], construction operations training [91,92], construction management training [93–95], and task execution training [22,23,33,96–98]. VR-based safety training has been shown to be sufficient and acceptable in simulating construction sites and promoting learning and knowledge retention [13,30,32]. Other than promoting learning and, consequently, improved safety behavior among construction workers, VR-based safety training has also been shown to enhance safety motivation and self-efficacy in identifying safety hazards, with perceptible effects on safety behaviors in both the short term and long term (knowledge retention) [32]. VR-based safety training has also been associated with improving safety behavior to a greater extent among non-experts than among experienced field personnel, which shows its potential in training incoming construction workers [86]. This is an important result, especially considering the construction industry's need to attract young workers to fulfill many of the currently open job positions in construction sites.

In training construction workers, the education research field has shown that VR can help workers develop skills/acquire knowledge within simulations and then successfully apply those skills and knowledge in real-world settings as effectively or more effectively than workers learning through other means [15,31]. In this context, in-person training in real-world contexts does not provide a significant advantage over learning these skills in virtual contexts [34]. In making this argument, construction education researchers also posit several benefits to VR training over traditional classroom pedagogies, on job training. First, VR simulations create a risk-free environment where workers can fail without injuring themselves or others [99,100]. Second, simulations provide workers with the affordance of immediate feedback (including haptic feedback) rather than having to wait for an individual to comment on their work [101–103]. Together, VR simulations provide a highly effective means for developing technical skills related to construction tasks without the added stressors of potentially injuring someone or chaotic environments [22]. More recently, companies such as 3M™ [104], Caterpillar® [105], Volvo [106], and Komatsu™ [107], and specialized training companies such as PIXO™ [108], Antycip [109], and Immersive Technologies [110], have developed and offered VR-based training programs for construction professionals focusing on safety and/or heavy-machine operations.

Combined with the on-demand nature of VR [111], VR presents a potentially democratizing tool in vocational training within the construction industry, one that may allow more workers in more places to develop much-needed technical skills. However, researchers and professionals cannot reach this goal without carefully thinking through how to implement VR best and design realistic, interactive, and effective VR simulations intentionally. As numerous authors have noted, developing effective VR simulations inherently involves interdisciplinary partnerships between educators, industry professionals, and software engineers [41,112,113]. Once designed, continued research into these tools needs to occur to determine the effectiveness of these simulations and the pedagogical implementation of VR in situ.

There are, however, many unanswered questions when it comes to training construction workers to work and/or interact with teleoperated robots in the construction industry using VR-based environments. First, to the best of our knowledge, no study has been conducted on the instruction of construction workers in how to teleoperate construction robots using VR-based environments. Therefore, research into construction training programs has overlooked the potential of using VR-based training to improve workers' knowledge, operational skills, and safety behavior during human-robot interaction on construction sites. In addition, even in the studies that have addressed the use of VR-based environments to train construction workers in the operation of construction machines, transfer of the acquired skills and safety behavior from the virtual environment to real-world applications using the actual machines has not been investigated.

This study addresses these gaps by providing new research into a VR-based training program explicitly dedicated to learning how to teleoperate robots within construction contexts. Differently than the most commonly found construction equipment used in many of the existing studies, e.g., excavators and cranes in which an operator controls the equipment from a cabin in the equipment, the selected demolition equipment used in this study can be classified as a robot (teleoperated system) according to the definition found in Saidi et al. [114]. Additionally, this study provides valuable insight into the need for reskilling and upskilling workers in the wake of increased automation within the construction industry.

3. Methods

3.1. Use case

To investigate our research questions, we have chosen a teleoperated demolition robot manufactured by Brokk Inc. Construction workers are exposed to more challenging and hazardous work conditions (e.g., extreme weather conditions, dust, collapses, radioactivity contamination) in demolition tasks than other construction jobs [115]. Therefore, teleoperated demolition robots are employed faster than other types of robots on construction sites to enhance safety and productivity. This type of robot constitutes about 90% of the construction robotics' total market [116]. Teleoperated demolition robots can access spaces out of reach or hazardous for workers (e.g., nuclear sites) as workers can remotely execute demolition tasks safer and faster using demolition robots. Since the operator has the most control over the robot on the construction sites, it is critical to train operators to ensure the safety and efficiency of the working environment. For instance, we need to teach operators the safe distance to operate the robot, and they need to learn the emergency tasks to execute when a construction worker enters the danger zone. In this study, we have developed and studied the impact of VR-based training for workers to teleoperate the demolition robot. However, construction workers working in the robot's vicinity also need safety training, but this training is more straightforward than the training of the operators.

Brokk Inc. is the leading manufacturer of demolition robots, with over 7,000 robots used in different projects worldwide. Brokk demolition robots consist of a body connected to an arm system, four legs (outriggers), and two continuous tracks (Figs. 1a and 1b). The arm system consists of arms that give the robot multiple degrees of freedom. Workers can attach different tools to the arm system (e.g., hammer, crusher, bucket, grapple). Outriggers help the robot stand stable while demolishing, and tracks allow the robot to move freely on the job site. The demolition robot is teleoperated through a controller by one construction worker. The worker teleoperates the robot standing at a safe distance from the robot, usually at its cornerback.

3.2. Experimental procedure

The study was conducted with 50 construction workers who completed a written informed consent before starting the experiment. Next, participants' backgrounds and demographics were measured by a set of survey items. Specifically, participants were asked to report their gender, age group, race, and the language they are comfortable speaking. The survey also measured participants' education level, employment status, and experience in the construction industry. Participants have also reported if they have any experience in using VR or demolition robots. Then, participants were required to complete a knowledge assessment survey including 32 multiple choice questions measuring participants' knowledge about teleoperating the demolition robot safely. Once the knowledge assessment survey was completed, participants were randomly assigned to one of the two conditions: 25 participants were asked to complete the VR-based training, while the other 25 were asked to complete the in-person training. After both groups completed their training, they were asked to retake the knowledge assessment survey to record the variations in their knowledge of teleoperating the demolition robot. In the last step, both groups of participants had to take a performance assessment, each participant completing the given tasks while teleoperating the actual demolition robot. The trainer rated participants' operational skills and safety behavior. Additionally, the trainer recorded his observations of participants' performance in teleoperating the demolition robot. Once the performance assessment is completed, the participants were thanked and dismissed.

3.3. VR-based training (Treatment intervention)

3.3.1. VR-based training system setup

Our VR-based training was developed using the Unity3D game

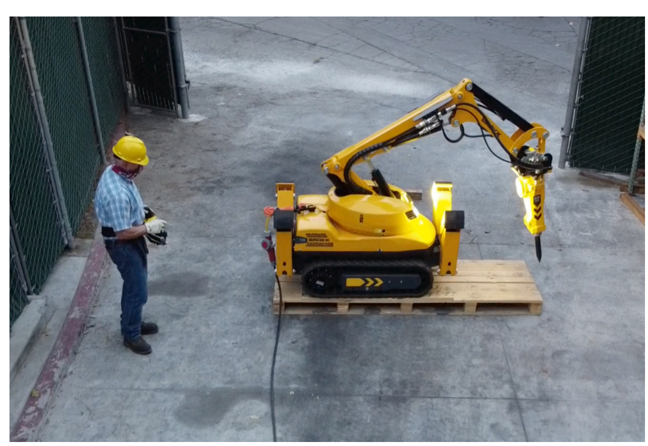


Fig. 1a. Actual Brokk demolition robot.

Fig. 1b. Simulated Brokk demolition robot.

engine on a PC with an NVIDIA GeForce GTX 1080 graphics card (Fig. 2b). For this 2-hour long training, we have simulated a dynamic construction site, including virtual construction workers using different sets of construction equipment working in a shared space (Fig. 2a). Our virtual construction site includes various work conditions such as dust, rainy and sunny weather conditions, and uneven terrain to deliver trainees a realistic experience of an actual job site. We have programmed the behavior of the demolition robot and objects in the virtual construction site using the C# programming language. Trainees interact with virtual objects and workers using the HTC Vive controller. Besides, HTC Vive Head Mounted Display (HMD) provides trainees a sense of presence and a full-immersion experience during training. We have modeled the controller of the demolition robot using the same body (buttons and levers) of the actual controller and have connected it to the PC using Arduino Pro micro serial connection. Since workers need to move the robot and teleoperate it in various locations on the construction site, we have used the Virtuix Omni VR treadmill as the navigation tool for trainees (Fig. 2c). VR treadmill using full-body motion tracking provides the advantage of navigating freely in the virtual dynamic construction site without the need to use controllers or keyboards. Our VR-based training incorporates different learning scenarios, which allow trainees to interact with different virtual objects and construction workers. To provide trainees realistic and immediate feedback throughout the training, we have incorporated Particle Systems API for visual effects (e.g., wall thickness, surface materials), VR Audio Spatializer for audio effects (e.g., demolition sounds), and physical simulations for materials (e.g., rigid bodies, joints, characters, robots).

3.3.2. VR-based training content

We have taken multiple steps to develop the learning modules of our VR-based training so that the program's content targets the key content and skills workers need to teleoperate the robot safely and effectively. We ran a focus group interview with six expert trainers to ensure that our learning modules are generalizable across trainers. An expert trainer also trained our research team through in-person training, so we can record topics covered in a typical training and in-person training delivery method. We then developed learning modules of our VR-based training using manuals of the demolition robot provided by the manufacturer, along with the analysis of the data we collected through focus groups and in-person training sessions. Since the median age of the labor force in the North American construction industry is 42.9 years [117], we developed learning modules based on andragogy learning theory principles, one of the major adult learning theories. Adult learners are self-directed and independent, with a wealth of experience to draw upon when learning, adult learners come with a readiness to learn that is driven by their social and occupational roles, a greater interest in problem-solving, and motivated by their need to immediately see the relevance of what they learn to the task at hand [72,73]. The detailed discussion on integrating andragogy learning theory and adapting useful features of previous VR-based training programs to our learning modules can be found in one of our studies [118]. We enhanced our learning modules, ensured that the VR-based training learning content is the same and in parallel to the in-person training, and prevented missing any critical learning content by collecting feedback from expert trainers in 3-months intervals. Moreover, before starting the experiment, we ran a pilot study to prevent potential technical issues such as the malfunction of the hand-held VR controller and the accuracy of the simulated demolition robot's controller. In the final step, an expert trainer verified our developed learning modules for the experiment.

We developed seven interactive scenario-based learning modules in two languages (English and Spanish) (as described in Table 1) to train workers for operational skills and safety behavior while teleoperating a demolition robot. The Hispanic/Latino construction workers who are more comfortable speaking Spanish than English have the option to receive the training in their native language. Since we have implemented a self-directed learning approach (andragogy) to our modules, trainees are able to go back and forth at their own pace in the learning scenarios. Besides, if trainees do not have the literacy to read, they can use the narration for the same learning content. As mentioned in Section 3.3.1., our VR-based training gives immediate feedback to the trainees based on their performance in learning modules. For example, if the trainee violates the safety zone boundaries (taught in learning module 2), the program automatically prompts a warning message explaining the operator's unsafe behavior (Fig. 3a). As another example, if trainees miss any steps in starting the controller and demolition robot, the

Fig. 2a. Construction site in the VR environment.

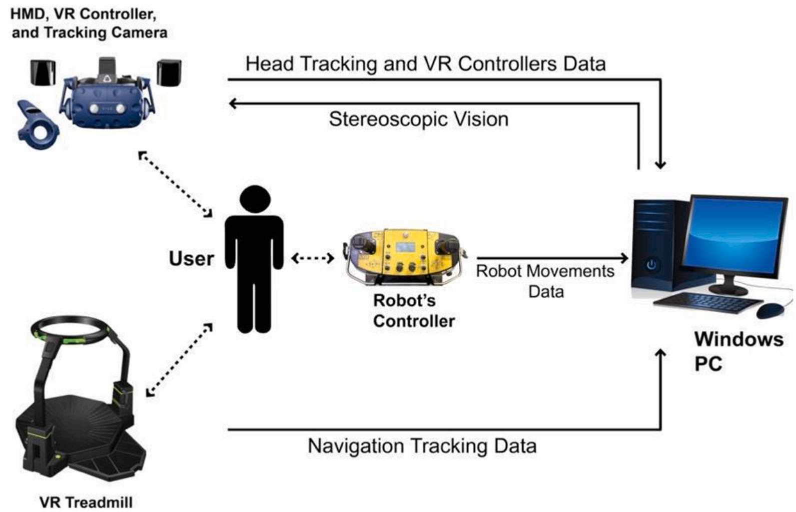


Fig. 2b. System setup.

Fig. 2c. Trainee on a VR treadmill.

program warns trainees about the mistakes they have made to correct them. Construction workers have a reservoir of experiences such as managing power cables, different interactions on job sites, and demolition procedures, which can be used as a rich resource for learning. Therefore, including tasks where they can draw upon their experiences can augment their learning. Moreover, our VR-based training provides the opportunity for trainees to practice with the demolition robot in the virtual construction site and execute tasks using different strategies based on the learning content and their prior experience and background knowledge (Fig. 3b). Trainees experience the consequences of their decisions while teleoperating the robot in the virtual environment without causing any damage to themselves or the actual robot. For example, if trainees do not put the arm system of the demolition robot in a safe position and stretch the arms while moving (practicing in learning module 6 – Table 1; the robot will tilt (Fig. 3c), and trainees will experience the consequence of their unsafe behavior in the virtual environment. Also, in learning module 7 (Table 1), trainees can use different strategies in demolishing a concrete block to experience which strategy is safer and more effective. It is improbable to expose trainees to hazardous working conditions and teleoperate the robot with potentially unsafe approaches in the in-person training. Simulating various working conditions in our virtual construction site prepares trainees to work in potential hazardous job sites. Trainees can teleoperate the demolition robot in different weather conditions (Fig. 3d), indoor vs. outdoor spaces, on inclined or uneven terrains, and most importantly, in a shared space with other virtual construction workers. Concerning the advancement of automation in construction sites, workers' learning needs are closely related to their job goals. Also, construction workers as adult learners are problem-centered and interested in immediately applying the acquired skill and knowledge. Hence, our learning modules provide skills and knowledge immediately applicable to the demolition teleoperation, and trainees acquire new skills to work with new technologies related to changing their roles. Trainees practice how to teleoperate the robot effectively and safely in simulated dynamic, unstructured construction sites. At the end of each learning module, trainees are evaluated to ensure that they have learned essential points about operational skills and safety behavior. If they fail in assessments, they can repeat the learning module and redo the tasks until they gain an acceptable level of skills and safety behavior. For example, at the end of learning module 3, the program requires trainees to move specific parts of the demolition robot, and if they fail in completing the task successfully, they need to review the learning content regarding controller functions. Adult learners are motivated to learn by internal rather than external forces. By giving an introduction and essential application of teleoperated robots in our learning modules, we try to elevate construction workers' interest to adapt themselves to the advancement of technology. The VR-based training takes 120 min to complete. Table 1 summarizes the targeted operational skills and safety behavior in each of the seven modules. A detailed description of the modules is provided in [118].

3.4. In-person training (Control intervention)

3.4.1. In-person training set up

In-person training with similar content and duration was provided to workers to assess the impact of the VR-based training on workers' knowledge and skills compared to the traditional in-person training method. In-person training sessions were held with around six to seven workers, one expert trainer, and the actual demolition robot lasting two hours (Fig. 4). In-person training sessions were held in an outdoor area of about 700 sqft, at the Department of Civil & Environmental Engineering at the University of Southern California. Brokk demolition robots have different sizes; however, we used Brokk110 (same as the robot size used in VR-based training) with a hammer and bucket for in-person training sessions. The professional trainer was provided with necessary objects to demonstrate the operation and train workers in a standard in-person training format. We simulated a concrete block with steel plates so the trainer could show the robot's correct and safe positioning to

Table 1
Targeted operational skills and safety behavior in each learning module.

Mod. #	Targeted Operational Skills	Targeted Safety Behavior
1	Introduction to the robot, its purpose, different applications, different components, and their detailed explanation	Introduction to the range of motion for each component
2	Operator positioning to have the best view and control during operation & how to move the robot (e.g., whether or not the robot can be maneuvered to fit in the workspace)	Cable safety management (e.g., the cable should not be on wet surfaces, near sharp objects, outriggers, and cable should be undamaged and behind the robot). Definition of operating zone and risk zone and boundary conditions for the risk zone. Workplace inspection (e.g., keep robot out of dust and flying rocks, be aware of personnel; turn off the robot in the event people enter the operating zone)
3	How to use the control unit (e.g., controller's setting, how to use each lever/button, etc.)	How to use the controller levers smoothly to move the robot's components safely and at a controllable pace.
4	How to start the control unit and the robot	Safety checks before starting the robot (e.g., check the hydraulic fluid level, ensure that there is no oil leakage, check if power and control cables are connected, inspect for loose objects on the robot, and check the emergency stop button of the control unit)
5	How to position the robot (e.g., demolition robot should not be too close to the object, the distance between the robot and other objects must be considered, optimum operating position for the arm system)	How to position the robot safely (e.g., robot's arms should not be fully extended; angles between cylinders should be within an acceptable limit)
6	How to move the robot, use the outriggers to position and stabilize the robot, and move the arm system via different simulated activities	Safety concerns during movement of the robot (e.g., avoiding the danger of tilting the robot; robot must be secured if there is a risk of collapsing/tilting)
7	How to demolish concrete slabs, floors, walls, beams, and columns effectively (e.g., the direction of demolition tools and demolition process and sequence, demolition starting points, demolition in one direction and sections, demolish the entire section within the working zone before moving the robot, etc.)	How to demolish concrete slabs, floors, walls, beams and, columns safely (e.g., positioning of the hammer to prevent harmful bounces, levers movement speed to have the best control on delicate demolition tasks, working using sight and hearing, etc.)

demolish a block.

3.4.2. In-person training content

A professional trainer developed the in-person training based on his experience in training workers for demolition robot teleoperation. While the learning content of both VR-based and in-person training was identical, the lessons of in-person training were not specially designed based on adult learning theory (andragogy). These lessons were the trainers' regular lessons, and the researchers did not change the design of these lessons. The trainer began the training by verbally introducing the history and applications of the demolition robot. Like VR-based training, module 1 (Table 1), trainees receive detailed information of the robot's various components. Then, the trainer described how to manage safety concerns while demonstrating with the actual robot, such as power-cable management and the robot's operation zone (VR-based training; module 2). As the content of the VR-based training, module 4, he presented the actual steps in checking safety points before starting and steps to start the controller and the robot. Next, the trainer demonstrated different controller functions to move the robot (VR-based training; module 3). He also showed the trainees how to move the robot safely, preventing tilting (VR-based training, module 6). He showed how to position the robot for demolition (VR-based training, module 5), stabilizing it using its outriggers, and the safe and effective strategies to demolish a concrete block, like the last learning module of the VR-based training (VR-based training, module 7). After the demonstration and a Q&A session, trainees had the opportunity to work with the actual controller and the demolition robot. However, since there was one robot and multiple trainees, they had limited time to practice with the robot. Besides, trainees were limited in performing various maneuverings in robot teleoperation since they may cause damage to the actual robot and themselves. As the trainees practiced teleoperating the robot, the trainer provided feedback to trainees about their operational skills and safety behavior.

3.5. Performance assessment

3.5.1. Performance assessment set up

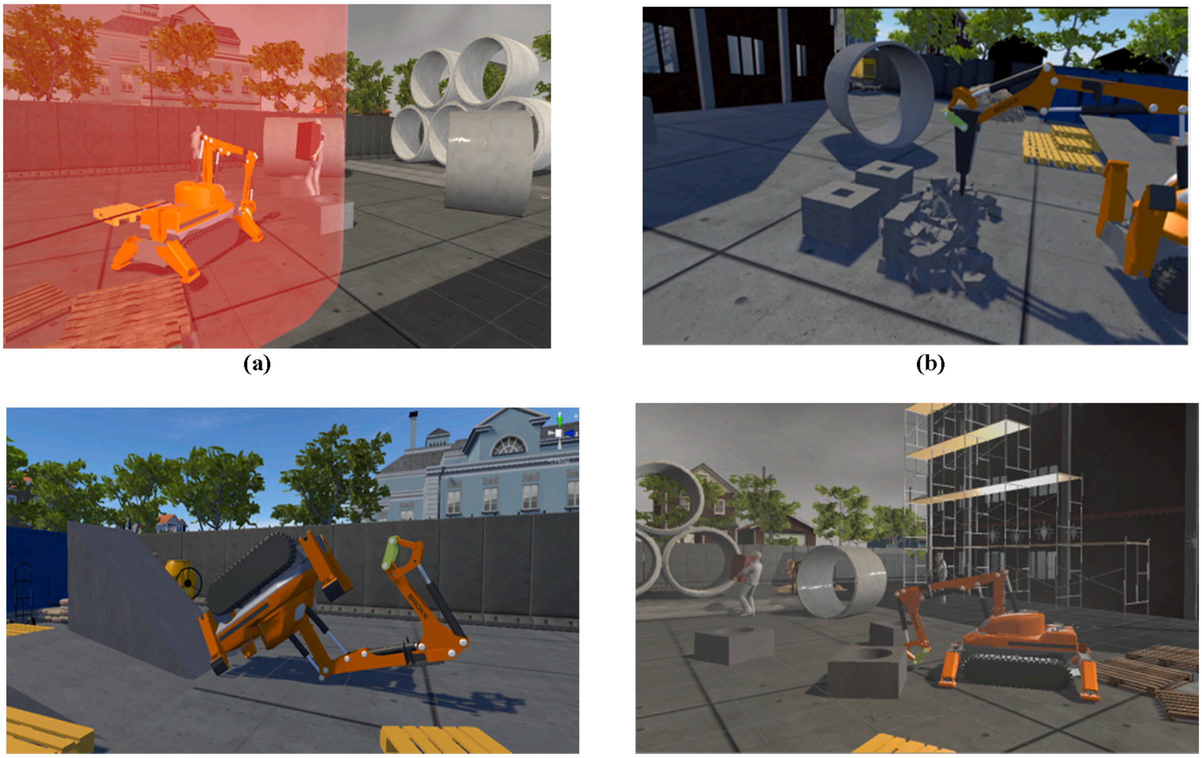
As mentioned earlier in Section 3.2 (experimental procedure), after both groups of participants (VR-based vs. in-person) finished their training, they completed a performance assessment during which each worker's operational skills and safety behavior was evaluated while teleoperating the actual robot (Fig. 5). This assessment took place at the same outdoor area in which in-person training sessions occurred. Different objects (e.g., boxes, sharp objects) were put in the environment to evaluate participants' operational skills and safety behavior while working with the robot. The trajectory to move the robot was indicated on the ground. Also, at the end of the route, we had simulated a concrete block using steel plates so participants could position the robot and demonstrate the demolition process. The performance assessment was held with one participant and one trainer at a time, lasting about 30 min for each participant.

3.5.2. Performance assessment content

In performance assessment, participants first were asked to start the robot and run the sequence of pre-start-up safety checks (e.g., hydraulic oil level, oil leakage, cable position). After starting the controller and the robot, participants moved the robot in the direction indicated on the ground. They had to know the controller's function and follow the safety rules to move the robot efficiently and safely. One of the safety concerns is that the worker should look at the robot during robot teleoperation to prevent accidents. Therefore, the worker has to know the function of the controller without needing to look at it. Besides, the smoothness of using the controller's levers is another factor for acceptable operational skills. The worker needs to push the levers smoothly to gain more speed in moving the robot's arm system. Participants have to move the robot while keeping a safe distance from surrounding objects and safely orient the arm system to avoid the robot's tilting. Participants then were asked to demonstrate how to position the robot and its arm system to demolish a concrete block based on the operational skills and safety points they had learned during their training. After the demonstration, participants were asked to move the robot in reverse to the starting position and complete the shutdown procedure.

3.6. Participants

A total of 50 participants (48 males, 2 females) were recruited for the experiment from on-campus construction projects at the University of Southern California. Since the training is designed to train construction workers (both current demolition workers and general construction workers) to teleoperate a demolition robot, all participants were construction workers over 18 years old with varying degrees of experience. They were randomly assigned to receive either VR-based or in-person training (25 participants for each group). One VR-based training participant quit the study since he could not use the VR-based equipment; therefore, we used the data from 49 participants in our analysis.



(a) (b) (c) (d)

Fig. 3. **(a)** Illustration of risk zone boundary and consequence of violating it **(b)** Demolition of concrete slabs (**c**) Simulating consequence of tipping the robot **(d)** Construction site in rainy weather in VR environment.

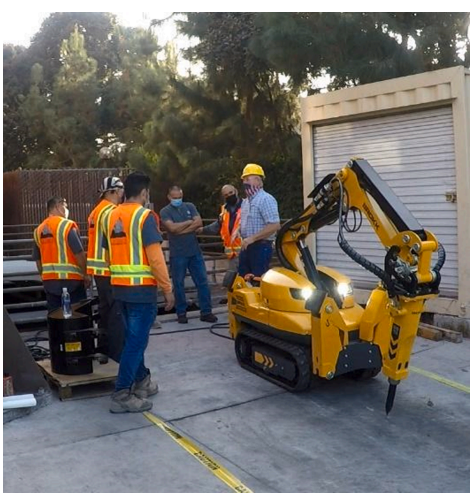


Fig. 4. Workers during an in-person training session.

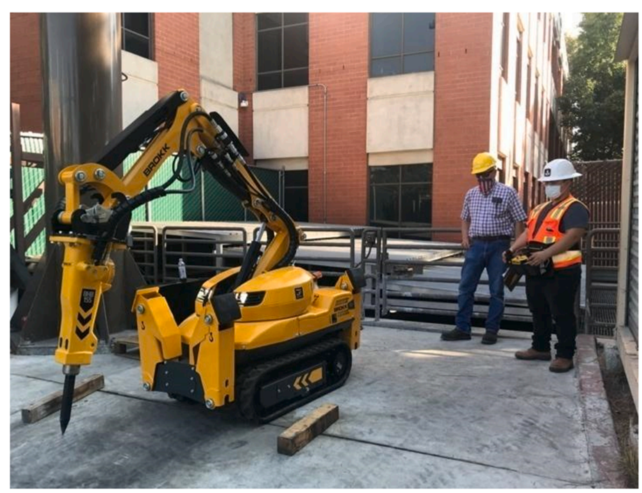


Fig. 5. Performance evaluation.

Table 2 presents the demographic information of the participants based on their age, language, education level, and their years of experience in the construction industry. None of the recruited participants had previous experience with the demolition robot used in the experiment or VR-based training. Only one participant from the in-person training group had a previous experience with a demolition robot (not the demolition robot used in this study); however, the answer to this question was not an exclusion criterion for the study.

3.7. Evaluation measures

To answer our first research question, we assessed trainees' knowledge acquisition before and immediately after completing either VR-based or in-person training. Therefore, we developed a knowledge assessment survey including 32 items to measure participants' knowledge about all aspects of the demolition robot, including components of the robot, risk zone, power cable management, workplace inspection, safety checks, controller functions, starting up the controller and the robot, arm positioning requirements, actions to be taken when demolishing, safety precautions and actions. The content of the items was validated by receiving feedback from an expert trainer to ensure that the critical knowledge needed to perform the robot safely was being assessed.

To answer our study's second and third research questions, we assessed trainees' operational skills and safety behavior while teleoperating the actual demolition robot (i.e., performance assessment).

Table 2
Demographics of participants based on training types.

Demographics	VR-based training	In-person training
Language		
English	12 (24%)	12 (24%)
Spanish	13 (26%)	13 (26%)
Age groups		
18–29	9 (18%)	7 (14%)
30–39	7 (14%)	7 (14%)
40–49	2 (4%)	4 (8%)
50–69	7 (14%)	7 (14%)
Education levels		
Less than a high school diploma degree	9 (18%)	10 (20%)
High school diploma degree	12 (24%)	12 (24%)
College degree	4 (8%)	3 (6%)
Construction Experience		
<5 years	12 (24%)	10 (20%)
5–10 years	6 (12%)	8 (16%)
>10 years	7 (14%)	6 (12%)

We developed the operational skills and safety behavior assessments used in this study, and an expert trainer validated the content of the assessments to ensure that all the crucial points are included. Participants' operational skill performance and safety behavior were rated based on the criteria by the expert trainer on a scale from 1 to 3 (1 = failed, 2 = done to an extent, 3 = perfectly done). Operational skills were observed and evaluated during starting up the controller and the robot, positioning the robot and the operator, using the controller (its buttons and levers) to move the robot, and employing an effective demolition strategy with a proper sequence. Safety behaviors were observed and evaluated during performing pre-start-up checks and workplace safety checks, moving the robot (e.g., keeping a safe distance from surrounding objects), and demolishing (e.g., moving arm system smoothly for delicate demolition tasks). The expert trainer also qualitatively measured participants' performance in teleoperating the robot. The trainer wrote a brief observation of each assessment that described positive and negative aspects of the participants' safety behavior and operational skills in working with the robot.

3.8. Analysis

This study relied on a quantitative dominant mixed methods approach to collecting and analyzing data to answer our research questions. Johnson et al. define the quantitative dominant mixed methods research as *"the type of mixed research in which one relies on a quantitative, post positivist view of the research process, while concurrently recognizing that the addition of qualitative data and approaches are likely to benefit most research projects"* [119]. Therefore, our analysis relies heavily on the quantitative data collected in this study, while our qualitative data primarily provides valuable context for our findings.

3.8.1. Quantitative analysis

The quantitative data collected were used to understand the impact of VR-based training on the traditional training methods (in-person training) on three dependent variables: knowledge acquisition, safety behavior, and operational skills while working with the demolition robot. For knowledge assessment, we conducted 2 × 2 mixed factorial ANOVA with time (pre-vs. post-training) as the within-subject factor and training type (VR-based training vs. in-person training) as the between-subject factor. Also, we conducted independent sample t-tests with training type (VR-based training vs. in-person) as the independent variables for each of operational skills and safety behavior outcomes. We then ran additional tests to check for moderation by demographic factors: in separate mixed ANOVAs, we tested for moderation by 1) language (Spanish vs. English), 2) age, 3) level of education, and 4) experience in the construction industry.

3.8.2. Qualitative analysis

To analyze the qualitative data collected in this study (specifically, the written observations from the expert trainer), we relied on a grounded theory approach articulated by Glaser and Strauss [120]. Because grounded theory intentionally situates all findings and theory within collected data (as opposed to applying theoretical frameworks from other sources), this methodological approach produced a detailed understanding of the impacts of training methods on participants' performance in this specific context [121]. Once we collected our qualitative data, we coded the expert trainer's observations through an iterative and open process. We began by employing a descriptive coding technique to produce a set of themes that our expert trainer discussed across the entire collection of observations [122]. After this first coding round, we then engaged a pattern coding strategy to condense our initial themes into analytical units and further illustrate any patterns within the data [123]. Two research team members have coded the qualitative data to ensure that Inter-Rater Reliability (IRR) is satisfied (>0.81).

4. Results

4.1. Qualitative analysis: VR-based training's impact on workers' knowledge, operational skills, and safety behaviors

As shown in Table 3, workers' knowledge in both programs increased after they completed the training. The average gain in knowledge was greater among those who completed the VR-based training (60.22%) than those who completed in-person training (39.55%) ($F(1,47) = 18.36$, $p < 0.001$, Cohen's $d > 1.0$) (Fig. 6). Of all the background indicators, only the moderating effect of age approached significance ($F(3,43) = 10.18$, $p = 0.08$; all other were nonsignificant $Fs < 0.31$, $ps > 0.58$)

Analyses of the participants' safety behavior assessment are presented in Table 4. Results indicate that VR-based training participants (mean rating: 2.60) have significantly better safety behavior in operating the robot than in-person training participants (mean rating: 2.30) ($t(47) = 3.985$, $p < 0.001$, Cohen's $d > 1.0$) (Fig. 7). Similar to the

Table 3
Means and standard deviations of knowledge assessment based on individual differences.

Measures	VR-based training		In-person training	
	Before	After	Before	After
Language				
English	9.26	74.74	8.11	55.73
	(8.57)	(9.37)	(9.20)	(16.69)
Spanish	10.16	65.11	14.75	46.87
	(9.98)	(15.24)	(14.63)	(17.44)
Age groups				
18–29	5.99	75.70	9.84	60.71
	(6.10)	(10.21)	(10.11)	(15.18)
30–39	12.63	72.32	9.93	50.45
	(11.28)	(11.04)	(14.75)	(13.55)
40–49	10.93	67.19	21.98	53.91
	(11.06)	(17.56)	(16.03)	(14.39)
50–69	11.46	59.37	9.04	40.63
	(10.21)	(3.95)	(9.73)	(15.73)
Education levels				
Less than a high school	12.54	64.45	9.78	40.94
diploma degree	(10.45)	(14.75)	(13.17)	(13.61)
High school diploma	9.20	69.27	13.87	56.25
degree	(8.83)	(10.48)	(13.15)	(18.08)
College degree	5.56	82.82	8.43	64.59
	(7.11)	(12.10)	(9.68)	(4.77)
Experience groups				
<5 years	12.01	69.27	7.26	44.69
	(10.31)	(15.41)	(6.02)	(20.63)
5–10 years	6.39	73.44	11.00	57.03
	(6.47)	(12.77)	(10.18)	(11.66)
>10 years	8.41	67.71	21.50	57.81
	(8.83)	(10.39)	(19.03)	(13.65)

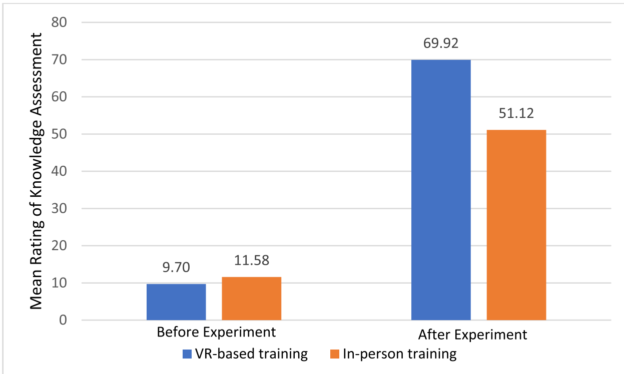


Fig. 6. Workers' average score on the knowledge assessment.

Table 4
Means and standard deviations of safety behavior assessment based on individual differences.

Measures	VR-based training	In-person training
Language		
English	2.62 (0.16)	2.40 (0.29)
Spanish	2.57 (0.25)	2.20 (0.28)
Age groups		
18–29	2.60 (0.16)	2.39 (0.21)
30–39	2.55 (0.18)	2.36 (0.36)
40–49	2.73 (0.11)	2.35 (0.21)
50–69	2.58 (0.32)	2.11 (0.31)
Education levels		
Less than a high school diploma degree	2.53 (0.26)	2.19 (0.28)
High school diploma degree	2.61 (0.20)	2.37 (0.30)
College degree	2.68 (0.08)	2.36 (0.30)
Experience groups		
<5 years	2.57 (0.21)	2.19 (0.33)
5–10 years	2.62 (0.19)	2.40 (0.30)
>10 years	2.61 (0.25)	2.37 (0.20)

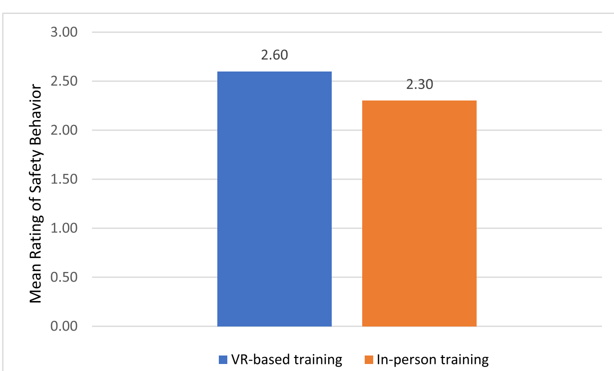


Fig. 7. Mean rating of safety behavior assessment.

knowledge assessment, of all the background indicators, only the moderating effect of age approached significance ($F(1,49) =$, $p < 0.001$; all others were nonsignificant $Fs < 0.29$, $ps > 0.36$).

Analyses for the operational skills assessment are presented in Table 5. Similar to safety behavior, VR-based training participants (mean rating: 2.65) have showed significantly better skill sets than in-person training participants (mean rating: 2.29) ($t(47) = 5.11$, $p < 0.001$, Cohen's $d > 1.0$) (Fig. 8). None of the demographic variables significantly moderated this effect (all $Fs < 1.15$, $ps > 0.29$).

Table 5
Means and standard deviations of operational skills assessment based on individual differences.

Measures	VR-based training	In-person training
Language		
English	2.63 (0.15)	2.40 (0.30)
Spanish	2.66 (0.16)	2.21 (0.27)
Age groups		
18–29	2.62 (0.15)	2.39 (0.22)
30–39	2.59 (0.15)	2.37 (0.34)
40–49	2.75 (0.07)	2.34 (0.23)
50–69	2.63 (0.18)	2.10 (0.31)
Education levels		
Less than a high school diploma degree	2.65 (0.15)	2.19 (0.28)
High school diploma degree	2.63 (0.19)	2.39 (0.31)
College degree	2.60 (0.09)	2.37 (0.31)
Experience groups		
<5 years	2.65 (0.12)	2.19 (0.34)
5–10 years	2.65 (0.19)	2.40 (0.31)
>10 years	2.66 (0.20)	2.36 (0.19)

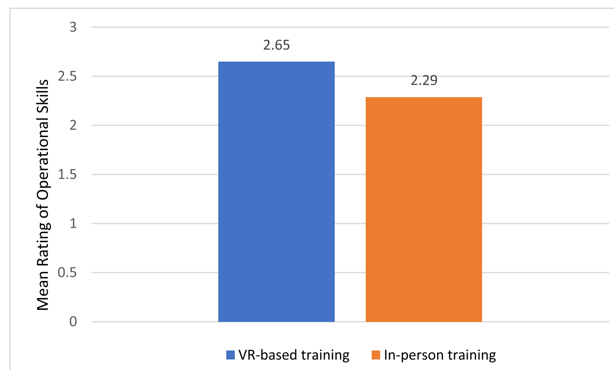


Fig. 8. Mean rating of operational skills assessment.

4.2. Qualitative differences in workers' performance

Qualitative results from the expert trainer's observations of participants' performance during demolition robot teleoperation are presented in Table 6. Our analysis identified three themes in the trainer's

Table 6
Themes, examples, and numbers of participants who got positive and negative comments based on their training type in the qualitative analysis.

Themes	Example	VR +	VR -	In-person +	In-person -
Pre-start-up checks	- Participant did excellent in remembering all the pre-start checks - Participant at first could not remember any of the pre-start checks	16	5	11	9
Controller usage	- Never looked at the controller, remembered controls pretty much w/o hesitation Repeatedly could not remember the functions	16	6	12	6
Moving the demolition robot	- Remembered the details of the safety points mostly w/o hesitation. - Same mistakes again and again; Doesn't understand the cautions and doesn't listen well to corrections	15	7	11	7

observations: pre-start-up checks, controller usage, and moving the robot while teleoperating the demolition robot. Table 6 presents each theme with examples of the trainer's comments and the number of positive and negative comments participants received based on their training type. For a few participants, the trainer did not have a comment on every theme.

The "pre-start-up checks" theme relates to the sequence of safety points that the participant needs to check before starting the robot. This was the first task that participants had to do regarding safety behavior in the performance assessment. The trainer commented on how the participants remembered the steps confidently and retained material about the checklist. The results indicate that VR-based training participants received more positive comments from the trainer in remembering and performing the safety checklist than the in-person training participants. Many of the VR-based training participants performed checks without hesitation or trainer prompting them.

The "controller usage" theme relates to participants' knowledge of the controller's functions and smoothly using the controller (levers and buttons) without looking at it. The results show that VR-based training had a better performance in remembering the controller's functions and using it without hesitations than in-person training participants. The trainer's feedback indicates that VR-based training participants smoothly moved the controller's levers and used the functions without hesitation.

The theme of moving the robot refers to the participant's performance in moving and orienting the robot effectively and safely. Similarly, VR-based training participants showed better performance in following safety guidelines and operational skills in moving the demolition robot than in-person training participants. Based on the trainer's comments, most of the VR-based training participants remembered the details of the safety points and positioned themselves for better vision during teleoperation, while some other participants made a few mistakes and needed coaching.

Two research team members independently coded for the three identified themes in the trainer's observations. Interrater reliability was assessed using the Kappa statistic [124] before both research members reconciled coding. The Kappa statistics calculated for both members were > 0.81, nearly perfect size, suggesting that the identified themes have high reliability.

5. Discussion

5.1. Knowledge acquisition

To explore possible reasons for the success behind this VR-based training in relation to knowledge acquisition, we contend that two key aspects of the design contributed to this success: the nature of the knowledge being learned and the use of learning theory within our curriculum design. Regarding the former, the process of using the demolition robot directly aligns with extant research into the use of VR simulations in educational contexts. For instance, previous studies have found that VR-based education works especially well when the content or skills being learned heavily rely on visual or spatial information or spatialization [55–57,76], and working with a demolition robot also depends on this type of information. Specifically, successfully teleoperating a demolition robot relies on workers seeing where the robot and its various elements are in relation to other elements in the environment. VR-based training illustrates all the essential knowledge about teleoperating the robot. Illustrations of robot components' movement range, risk zone and its boundaries, workplace inspection, safety management (e.g., power cable management), safe/dangerous movement of the robot and its failure, and safe/dangerous demolition strategies improve workers' knowledge acquisition and retention compared to in-person training. Due to safety, cost, and maintenance concerns, the trainer has restrictions illustrating all the critical information in the in-person training. Therefore, workers acquire a part of knowledge only verbally in the in-person training format. The effectiveness of transferring knowledge verbally is limited by communication skills between trainer and trainees. However, VR-based training eliminates language barriers existing in in-person training by integrating different languages. While VR-based training has advantages over in-person training, some disadvantages exist. Developing VR-based training, including accurate robot and construction job site simulations and visualizations, may need significant effort, time, and cost. However, this process can be a one-time effort applied to many training sessions, while there is a need for a trainer and an actual robot at all in-person training sessions. Another limitation of VR-based training is that running the training may need substantial computing power. However, as VR technology becomes common, development and running process costs decrease considerably.

However, the alignment between the knowledge of working with a demolition robot and VR-based training as a pedagogical model does not guarantee a successful training process. As Wikens and Chavez and Bayona show, the design of the VR program largely determines the success of a specific training process [39,40]. We relied on adult learning theory (andragogy) and extant research in VR education to create this specific set of learning modules (using the same contents of in-person training) that build on the strength of VR to create environments and experiences that model specific learning outcomes [67]. We only focused on integrating adult learning theory (andragogy) in VR-based training as we did not want to manipulate the existing in-person training method in the industry. For instance, we employed a self-directed approach to learning where trainees can go back and forth at their own pace, review learning materials, and practice the tasks multiple times. We also tested the trainees at the end of each module and had them review that section if they did not pass the test. This represents a distinct benefit over the in-person training, where individuals must work at the instructor's pace. Moreover, construction workers as adult learners have a reservoir of life experiences; we used this rich experience as a resource to design the tasks in VR learning modules. For example, asking the worker to manage the power cable based on the learning content helps the trainee draw on his/her previous experiences to improve the learning process. Regarding the advancement of automation on construction sites, workers require learning needs closely related to their job goals. Construction workers as adult learners are problem-centered and interested in directly applying the acquired skill and knowledge. Hence, we designed the VR-based training to provide skills and knowledge immediately applicable to the demolition teleoperation, and workers obtained new skills to work with new technologies related to adapting their roles. Adult learners are motivated to learn by internal rather than external forces. Therefore, we provided an introduction and essential application of teleoperated robots in VR-based training to elevate construction workers' interest in adapting themselves to the advancement of technology. Besides, giving immediate feedback to the workers based on their performance can help trainees who do not have all the characteristics of an adult learner and need direction throughout the training. To this end, we attribute the success of VR in this study to our use of research into VR education and adult learning theory (andragogy) in the design of this program. Therefore, we recommend that future design efforts draw from a similar research base.

5.2. Operational skills & safety behavior

In alignment with most of the existing research into the use of VR within vocational training (and construction training in particular), the findings from this study strongly assert the efficacy of VR-based training in developing construction workers' operational skills and safety behavior for interaction with construction robots. VR-based training participants had significantly better results regarding the development of operational skills and safety behavior while working with the robot; thus, VR not only provides a viable option for future training programs but one that could significantly improve workplace safety. VR-based programs also have the potential to support future construction robotics design and development by allowing end-users to interact with several prototypes in a simulated environment. Additionally, as multiple researchers have noted, VR also removes a number of barriers associated with in-person training related to cost, scheduling, and accessibility [66,75,111,125,126]. Our VR-based training increases uniformity, quality, and reliability across trainers. All the trainees get the exact same learning content in the VR-based training; however, this is not guaranteed in the in-person training. Additionally, VR-based training reduces the need for specialized training manpower; and provides the ability to reach trainees in places without access to trainers and/or equipment. This positions VR as a highly valuable option for the future of construction safety and skill training in terms of consistency, scalability, and scalability of this training technology.

We suspect that the VR training proved so successful because of two affordances associated with VR. First, the VR training modules align with previous research findings that connect learning within VR to the ability of participants to "fail" without serious consequences [127,128]. This is one of the main differences in the training style between VR-based and in-person training, although the learning contents are the same and in parallel. Training with a demolition robot connects with a number of reasons for using VR [54]: training with an actual demolition robot is dangerous, mistakes made with the demolition robot would be costly to both the machinery and the environment (allowing for a less stressful learning environment), and the use of the VR system holds just as much motivation for the learner as working with the machine (assuming that the motivation involves getting to work with new technology in general and not a specific machine). Importantly, this alignment between learning with the demolition robot and VR-based training models is not specific to this robot but instead applies to nearly all construction robots (most rely on visual/spatial information, most are dangerous or expensive to operate). Therefore, these findings from this study position VR-based training as a highly effective tool in improving operational skills and safety behavior using VR and vocational training for construction workers who want to learn how to interact with construction robots.

The hesitation and smoothness associated with working with the actual robot, a finding associated with the theme of "controller usage" and "moving the robot" in robot teleoperation that emerged within our qualitative analysis, points to this affordance. Since VR trainees did not feel as nervous working within this context, they could focus on skill and safety behavior development without worrying about damaging the robot. Second, the VR program we developed allowed workers to learn with the actual controller they would use. As Bhoir & Esmaeili [129] contend, the hesitation associated with adopting VR technology within training programs often stems from the trainer's assumption that VR does not provide a realistic experience for trainees. However, since we have simulated the construction site in various hazardous working scenarios and simulated the actual controller with realistic maneuvering of the robot, these points help improve that experience and more strongly align VR with real-world experiences involving the robot, leading to a high rate of transfer between contexts. Our findings also build on Mekacher's [65] assertion that VR-based training, while covering the exact contents of in-person training, allows for a certain amount of experimentation and opportunities for "failure" not available in in-person experiences. Similarly, the program also relied on the established idea within VR education that trainees can experience the consequences of their decisions without causing irreparable damage or harm [54]. For example, they could move the robot onto a dangerous steep surface and experience the robot tilting and falling without breaking the actual robot. This further builds on extant research into safety training for construction workers that uncovered the connection between knowledge acquisition and the ability to "fail" provided by VR [57,66]. Although VR-based training allows the trainee to practice with the robot in the VR environment, this training can have physical side effects on trainees such as dizziness, eyestrain, or nausea. In order to prevent participants from experiencing motion sickness, we asked them to take off the HMD after each learning module (for 5–10 min), and they did not move in the VR environment without physically moving themselves using the treadmill, as both of these are standards for minimizing motion sickness.

6. Limitations

While this study presents VR-based training implications for knowledge, operational skills, and safety behavior development in robotic teleoperation in the construction industry, some limitations exist. Although VR-based training has advantages in terms of safety, scalability, and overcoming language barriers, developing and running VR-based training requires significant effort and computing power. Besides, using VR-based training may have physical side effects. In future studies, researchers might compare the costs of implementing VR-based training compared to in-person training. While in-person training has costs such as potential workers injuries, potential damage to the robot, robot maintenance, hiring professional trainers, and disturbance of the work on construction site, VR-based training also has costs such as developing the virtual environment, required computational power, required hardware, and potential physical side effects (e.g., fatigue, dizziness, motion sickness).

Moreover, due to the limited resources in recruiting construction workers, renting the actual robot, and hiring a professional trainer for the experiment during the pandemic, we could hire only one professional trainer to evaluate trainees' performance with the actual robot, both quantitatively and qualitatively. Using a second evaluator can ensure having inter-rated agreement on the quantitative scores and qualitative assessment in future studies. Besides, we could not collect participants' perceptions of VR-based training due to the time limitation. We recommend future studies collect feedback from participants on their experience with VR-based training.

7. Conclusion

The present study makes an important contribution to existing research on VR-based training within the construction industry. We build on previous studies that examined the use of VR within safety training for construction workers by shifting the context towards technology and robotics training for the same population. Findings from this study indicate that VR-based training in this context was associated with a more significant increase in knowledge acquisition, operational skills, and safety behavior when compared to in-person training with the machine itself. In doing so, we position VR-based training as a valuable tool in developing workers' knowledge, ability, and safety behavior to implement robotics within the field of construction. In addition, this study positions VR-based training as an equally effective pedagogical model when compared to hands-on or in-person training, an insight that produces multiple (and substantial) implications for improving human-robot interaction using VR, especially in the construction field. First, VR-based training reduces the risk to both workers and machinery associated with in-person training since trainees cannot hurt themselves or damage the robot if they make a mistake during the process. Second, VR-based training holds the potential to reduce the costs associated with training significantly. While VR technology may not be universally accessible at this point (both in terms of physical access and cost), in-person training requires (at the very least) rental, transportation, and trainer fees for every single training session. Since the cost of VR technology continues to decrease, this approach to training provides an inexpensive, on-demand, and individualized alternative to traditional approaches to training. To this end, VR represents a safe and accessible format for construction training, one that the industry should further develop as the field increasingly adopts robots in real-world applications.

While this study holds several significant implications for knowledge, operational skill, and safety behavior development in human-robot interaction with a specific focus on construction research, some limitations do, of course, exist. This study relies on data generated by a limited number of participants. While the differences between training conditions were quite large, and therefore our effects were significant even with the small sample size, our study might have been underpowered to test for moderation (e.g., language, age groups, educational level). Besides, we did establish that knowledge of the robot's teleoperation was improved more by VR-based training than in-person training. However, we tested the improvement in participants' knowledge by measuring it before and immediately after the training. Future studies are needed to investigate whether they are maintaining such knowledge gains in the long run and to investigate the effectiveness of VR-based training on knowledge acquisition, operational skills, and safety behavior while working with the robot with a larger sample size. Beyond generalizability issues, using a larger sample size also allows for more detailed investigations into the differences between individuals to more accurately determine when and why VR works as a pedagogical model.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

This work was supported by the National Science Foundation under Grant No. 1822724, and the U.S. Army Research Office under Grant No. W911NF2020053. The help of Mike Martin, Michael Peschka, and the Brokk company throughout this research study is greatly appreciated. Any opinion, content or information presented does not necessarily reflect the position or the policy of the National Science Foundation's views, and no official endorsement should be inferred.

References

[1] P. Gerbert, S. Castagnino, C. Rothballer, A. Renz, R. Filitz, The Transformative Power of Building Information Modeling, Digit. Eng. Constr. (2016). https://www.bcg.com/publications/2016/engineered-products-infrastructure-digital-transformative-power-building-information-modeling.aspx (accessed January 2, 2020).

[2] U.S. BUREAU OF LABOR STATISTICS (BLS), Number and rate of fatal work injuries, by industry sector, (2020). https://www.bls.gov/charts/census-of-fatal-occupational-injuries/number-and-rate-of-fatal-work-injuries-by-industry.htm.

[3] S. Brown, R.D. Brooks, X.S. Dong, Nonfatal Injury Trends in the Construction Industry, (2020). https://www.cpwr.com/wp-content/uploads/DataBulletin-December2020.pdf.

[4] J. Davidson, Report of 10,000 severe workplace injuries might be only half the problem, Washington Post. (2016). https://www.washingtonpost.com/news/powerpost/wp/2016/03/18/report-of-10000-severe-workplace-injuries-might-be-only-half-the-problem/ (accessed March 1, 2021).

[5] U.S. Bureau of Labor Statistics, Table A. Job openings, hires, and total separations by industry, seasonally adjusted, (2021). https://www.bls.gov/news.release/jolts.a.htm (accessed April 15, 2021).

[6] F. Barbosa, J. Woetzel, J. Mischke, M.J. Ribeirinho, M. Sridhar, M. Parsons, N. Bertram, S. Brown, Reinventing Construction: A Route To Higher Productivity (Full Report), 2017. https://www.mckinsey.com/business-functions/operations/our-insights/reinventing-construction-through-a-productivity-revolution.

[7] M. Tanzini, J.M. Jacinto-Villegas, M. Satler, M. Niccolini, C.A. Avizzano, Embedded architecture of a hydraulic demolition machine for robotic teleoperation in the construction sector, IEEE Int. Conf. Autom. Sci. Eng. (2018) 506–513, https://doi.org/10.1109/COASE.2018.8560345.

[8] Robotics Business Review, More than 7,000 Robots Will Work in Construction by 2025, Report Says, (2019). https://www.roboticsbusinessreview.com/construction/more-than-7000-robots-will-work-in-construction-by-2025-report-says/.

[9] K. Ellingrud, R. Gupta, J. Salguero, Building the vital skills for the future of work in operations, McKinsey Co. (2020). https://www.mckinsey.com/business-functions/operations/our-insights/building-the-vital-skills-for-the-future-of-work-in-operations (accessed March 5, 2021).

[10] G. Burdick, Demolition Robots Pose Injury Hazards for Construction Workers, Facil. Manag. Advis. (2019). https://facilitiesmanagementadvisor.blr.com/design-and-construction/demolition-robots-pose-injury-hazards-for-construction-workers/ (accessed March 5, 2021).

[11] M.J. Burke, S.A. Sarpy, K. Smith-Crowe, S. Chan-Serafin, R.O. Salvador, G. Islam, Relative effectiveness of worker safety and health training methods, Am. J. Public Health. 96 (2006) 315–324, https://doi.org/10.2105/AJPH.2004.059840.

[12] I. Jeelani, K. Han, A. Albert, Development of virtual reality and stereo-panoramic environments for construction safety training, Eng. Constr. Archit. Manag. 27 (2020) 1853–1876, https://doi.org/10.1108/ECAM-07-2019-0391.

[13] R. Sacks, A. Perlman, R. Barak, Construction safety training using immersive virtual reality, Constr. Manage. Econ. 31 (2013) 1005–1017, https://doi.org/10.1080/01446193.2013.828844.

[14] S. Joshi, M. Hamilton, R. Warren, D. Faucett, W. Tian, Y. Wang, J. Ma, Implementing Virtual Reality technology for safety training in the precast/prestressed concrete industry, Appl. Ergon. 90 (2021), 103286, https://doi.org/10.1016/j.apergo.2020.103286.

[15] H. Li, G. Chan, M. Skitmore, Multiuser virtual safety training system for tower crane dismantlement, J. Comput. Civ. Eng. 26 (2012) 638–647, https://doi.org/10.1061/(ASCE)CP.1943-5487.0000170.

[16] A.A. Akanmu, J. Olayiwola, O. Ogunseiju, D. McFeeters, Cyber-physical postural training system for construction workers, Autom. Constr. 117 (2020), 103272, https://doi.org/10.1016/j.autcon.2020.103272.

[17] J.A. Diego-Mas, J. Alcaide-Marzal, R. Poveda-Bautista, Effects of using immersive media on the effectiveness of training to prevent ergonomics risks, Int. J. Environ. Res. Public Health. 17 (2020) 2592, https://doi.org/10.3390/ijerph17072592.

[18] X. Su, P.S. Dunston, R.W. Proctor, X. Wang, Influence of training schedule on development of perceptual–motor control skills for construction equipment operators in a virtual training system, Autom. Constr. 35 (2013) 439–447, https://doi.org/10.1016/j.autcon.2013.05.029.

[19] J.C.Y. So, R.W. Proctor, P.S. Dunston, X. Wang, Better retention of skill operating a simulated hydraulic excavator after part-task than after whole-task training, Hum. Factors. 55 (2013) 449–460, https://doi.org/10.1177/0018720812454292.

[20] J.R. Juang, W.H. Hung, S.C. Kang, SimCrane 3D+: A crane simulator with kinesthetic and stereoscopic vision, Adv. Eng. Informatics. 27 (2013) 506–518, https://doi.org/10.1016/j.aei.2013.05.002.

[21] H. Song, T. Kim, J. Kim, D. Ahn, Y. Kang, Effectiveness of VR crane training with head-mounted display: double mediation of presence and perceived usefulness, Autom. Constr. 122 (2021), https://doi.org/10.1016/j.autcon.2020.103506.

[22] R. Barkokebas, C. Ritter, V. Sirbu, X. Li, M. Al-Hussein, Application of virtual reality in task training in the construction manufacturing industry, ISARC. Proc. Int. Symp. Autom. Robot. Constr. 36 (2019) 796–803, https://doi.org/10.22260/ISARC2019/0107.

[23] M. Wolf, J. Teizer, J.-H. Ruse, Case study on mobile virtual reality construction training, ISARC. Proc. Int. Symp. Autom. Robot. Constr. 36 (2019) 1231–1237, https://doi.org/10.22260/ISARC2019/0165.

[24] P.S. Dunston, R.W. Proctor, X. Wang, Challenges in evaluating skill transfer from construction equipment simulators, Theor. Issues Ergon. Sci. 15 (2014) 354–375, https://doi.org/10.1080/1463922X.2011.624647.

[25] B.N. Bhalerao, P.S. Dunston, R.W. Proctor, Use of PC-based Simulators to train basic control functions of a hydraulic excavator: audiovisual instruction contrasted with hands-on exploration, Int. J. Hum. Comput. Interact. 33 (2017) 66–74, https://doi.org/10.1080/10447318.2016.1232230.

[26] C. Evia, Localizing and designing computer-based safety training solutions for hispanic construction workers, J. Constr. Eng. Manag. 137 (2011) 452–459, https://doi.org/10.1061/(ASCE)CO.1943-7862.0000313.

[27] U.S. Bureau of Labor Statistics, 18. Employed persons by detailed industry, sex, race, and Hispanic or Latino ethnicity, (2021). https://www.bls.gov/cps/cpsaat18.htm (accessed March 1, 2021).

[28] CPWR - The Center for Construction Research and Training, Hispanic Employment in Construction, CPWR Data Cent. (2009). https://www.elcosh.org/record/document/1686/d000989.PDF (accessed July 11, 2021).

[29] U.S. Bureau of Labor Statistics, Labor force characteristics by race and ethnicity, 2019, BLS Reports. (2020). https://www.bls.gov/opub/reports/race-and-ethnicity/2019/home.htm (accessed March 1, 2021).

[30] Z. Xu, N. Zheng, Incorporating virtual reality technology in safety training solution for construction site of urban cities, Sustain. (Basel, Switzerland). 13 (2021) 243, https://doi.org/10.3390/su13010243.

[31] L. Hou, H.-L. Chi, W. Tarng, J. Chai, K. Panuwatwanich, X. Wang, A framework of innovative learning for skill development in complex operational tasks, Autom. Constr. 83 (2017) 29–40, https://doi.org/10.1016/j.autcon.2017.07.001.

[32] M. Nykänen, V. Puro, M. Tiikkaja, H. Kannisto, E. Lantto, F. Simpura, J. Uusitalo, K. Lukander, T. Räsänen, T. Heikkilä, A.-M. Teperi, Implementing and evaluating novel safety training methods for construction sector workers: results of a randomized controlled trial, J. Safety Res. 75 (2020) 205–221, https://doi.org/10.1016/j.jsr.2020.09.015.

[33] F. Osti, R. de Amicis, C.A. Sanchez, A.B. Tilt, E. Prather, A. Liverani, A VR training system for learning and skills development for construction workers, Virtual Real. J. Virtual Real. Soc. (2020), https://doi.org/10.1007/s10055-020-00470-6.

[34] M.N. Sakib, T. Chaspari, A.H. Behzadan, Physiological data models to understand the effectiveness of drone operation training in immersive virtual reality, J. Comput. Civ. Eng. 35 (2021), https://doi.org/10.1061/(ASCE)CP.1943-5487.0000941.

[35] J.C.Y. So, L.M. Macrowski, P.S. Dunston, R.W. Proctor, J.E. Goodney, Transfer of Operator Training from Simulated to Real Hydraulic Excavators, (2016) 1968–1977. Doi: 10.1061/9780784479827.196.

[36] Y. Fang, Y.K. Cho, F. Durso, J. Seo, Assessment of operator's situation awareness for smart operation of mobile cranes, Autom. Constr. 85 (2018) 65–75, https://doi.org/10.1016/j.autcon.2017.10.007.

[37] Y. Fang, Y.K. Cho, Effectiveness analysis from a cognitive perspective for a real-time safety assistance system for mobile crane lifting operations, J. Constr. Eng. Manag. 143 (2017) 5016025, https://doi.org/10.1061/(ASCE)CO.1943-7862.0001258.

[38] I.M. Rezazadeh, X. Wang, M. Firoozabadi, M.R.H. Golpayegani, Using affective human–machine interface to increase the operation performance in virtual construction crane training system: a novel approach, Autom. Constr. 20 (2011) 289–298, https://doi.org/10.1016/j.autcon.2010.10.005.

[39] C.D. Wickens, Virtual reality and education, in: [Proceedings] 1992 IEEE Int. Conf. Syst. Man, Cybern. 1992: pp. 842–847 vol.1. Doi: 10.1109/ICSMC.1992.271688.

[40] B. Chavez, S. Bayona, Virtual Reality in the Learning Process, in: Á. Rocha, H. Adeli, L.P. Reis, S. Costanzo (Eds.), Trends Adv, Springer International Publishing, Cham, Inf. Syst. Technol., 2018, pp. 1345–1356.

[41] M. Fernandez, Augmented-Virtual Reality: How to improve education systems, High. Learn. Res. Commun. 7 (2017) 1, https://doi.org/10.18870/hlrc.v7i1.373.

[42] J.H. Kim, S.-T. Park, H. Lee, K.-C. Yuk, Virtual reality simulations in physics education, Interact. Multimed. Electron. J. Comput. Learn. 3 (2001) 1–7. http://imej.wfu.edu/articles/2001/2/02/index.asp.

[43] G. Makransky, S. Borre-Gude, R.E. Mayer, Motivational and cognitive benefits of training in immersive virtual reality based on multiple assessments, J. Comput. Assist. Learn. 35 (2019) 691–707, https://doi.org/10.1111/jcal.12375.

[44] R. Nori, L. Piccardi, M. Migliori, A. Guidazzoli, F. Frasca, D. De Luca, F. Giusberti, The virtual reality Walking Corsi Test, Comput. Human Behav. 48 (2015) 72–77, https://doi.org/10.1016/j.chb.2015.01.035.

[45] V. Souza, A. Maciel, L. Nedel, R. Kopper, K. Loges, E. Schlemmer, The effect of virtual reality on knowledge transfer and retention in collaborative group-based learning for neuroanatomy students, SVR (2020) 92–101, https://doi.org/10.1109/SVR51698.2020.00028.

[46] C. Ekstrand, A. Jamal, R. Nguyen, A. Kudryk, J. Mann, I. Mendez, Immersive and interactive virtual reality to improve learning and retention of neuroanatomy in medical students: a randomized controlled study, C. Open. 6 (2018) E103–E109, https://doi.org/10.9778/cmajo.20170110.

[47] D.W.K. Man, W.S. Poon, C. Lam, The effectiveness of artificial intelligent 3-D virtual reality vocational problem-solving training in enhancing employment opportunities for people with traumatic brain injury, Brain Inj. 27 (2013) 1016–1025, https://doi.org/10.3109/02699052.2013.794969.

[48] S.J. Smith, S. Farra, D.L. Ulrich, E. Hodgson, S. Nicely, W. Matcham, Learning and retention using virtual reality in a decontamination simulation, Nurs. Educ. Perspect. 37 (2016) 210–214, https://doi.org/10.1097/01.NEP.0000000000000035.

[49] J. Zhang, Immersive Virtual Reality Training to Enhance Procedural Knowledge Retention, Purdue University Graduate School, 2019. https://hammer.purdue.edu/articles/thesis/Immersive_Virtual_Reality_Training_to_Enhance_Procedural_Knowledge_Retention/8307560/1.

[50] J. Bertram, J. Moskaliuk, U. Cress, Virtual training: Making reality work? Comput. Human Behav. 43 (2015) 284–292, https://doi.org/10.1016/j.chb.2014.10.032.

[51] A. Pedro, Q.T. Le, C.S. Park, Framework for integrating safety into construction methods education through interactive virtual reality, J. Prof. Issues Eng. Educ. Pract. 142 (2016) 4015011, https://doi.org/10.1061/(ASCE)EI.1943-5541.0000261.

[52] G. Wallet, H. Sauzéon, J. Rodrigues, B. N'Kaoua, Use of virtual reality for spatial knowledge transfer: effects of passive/active exploration mode in simple and complex routes for three different recall tasks, Virtual Real Softw. Technol. (2008) 175–178, https://doi.org/10.1145/1450579.1450616.

[53] G. Wallet, H. Sauzéon, J. Rodrigues, B. N'Kaoua, Transfer of spatial knowledge from a virtual environment to reality: impact of route complexity and subject's strategy on the exploration mode, JVRB - J. Virtual Real. Broadcast. 6 (2009) (2009), https://doi.org/10.20385/1860-2037/6.2009.4.

[54] V.S. Pantelidis, Reasons to Use Virtual Reality in Education and Training Courses and a Model to Determine When to Use Virtual Reality, Themes Sci. Technol. Educ. 2 (2009) 59–70. https://eric.ed.gov/?id=EJ1131313.

[55] S. Ahmed, A review on using opportunities of augmented reality and virtual reality in construction project management, Organ. Technol. Manag. Constr. 10 (2018) 1839–1852, https://doi.org/10.2478/otmcj-2018-0012.

[56] K.-T. Huang, C. Ball, J. Francis, R. Ratan, J. Boumis, J. Fordham, Augmented versus virtual reality in education: an exploratory study examining science knowledge retention when using augmented reality/virtual reality mobile applications, Cyberpsychol. Behav Soc. Netw. 22 (2019) 15–110, https://doi.org/10.1089/cyber.2018.0150.

[57] D. Zhao, J. Lucas, Virtual reality simulation for construction safety promotion, Int. J. Inj. Contr. Saf. Promot. 22 (2015) 57–67, https://doi.org/10.1080/17457300.2013.861853.

[58] L. Jensen, F. Konradsen, A review of the use of virtual reality head-mounted displays in education and training, Educ. Inf. Technol. 23 (2018) 1515–1529, https://doi.org/10.1007/s10639-017-9676-0.

[59] Q.T. Le, A. Pedro, C.S. Park, A social virtual reality based construction safety education system for experiential learning, J. Intell. Robot. Syst. 79 (2015) 487–506, https://doi.org/10.1007/s10846-014-0112-z.

[60] C. Sydora, Z. Lei, M.F.F. Siu, S. Han, U. Hermann, Critical lifting simulation of heavy industrial construction in gaming environment, Facil. (Bradford, West Yorkshire, England). 39 (2020) 113–131. Doi: 10.1108/F-08-2019-0088.

[61] B. Bogosian, L. Bobadilla, M. Alonso, A. Elias, G. Perez, H. Alhaffar, S. Vassigh, Work in Progress: Towards an Immersive Robotics Training for the Future of Architecture, Engineering, and Construction Workforce, in: 2020 IEEE World Conf. Eng. Educ., 2020: pp. 1–4. Doi: 10.1109/EDUNINE48860.2020.9149493.

[62] J. Spilski, C. Giehl, S. Schlittmeier, T. Lachmann, J.-P. Exner, A. Makhkamova, D. Werth, M. Schmidt, M. Pietschmann, Potential of VR in the vocational education and training of craftsmen, in: 19th Int. Conf. Constr. Appl. Virtual Real., 2019: p. 10. https://www.aws-institut.de/publikation/potential-of-vr-in-the-vocational-education-and-training-of-craftsmen/.

[63] R. Eiris, M. Gheisari, B. Esmaeili, Desktop-based safety training using 360-degree panorama and static virtual reality techniques: a comparative experimental study, Autom. Constr. 109 (2020), 102969, https://doi.org/10.1016/j.autcon.2019.102969.

[64] J. Tichon, R. Burgess-Limerick, A review of virtual reality as a medium for safety related training in mining, J. Heal. Saf. Res. Pract. 3 (2011) 33–40.

[65] D.L. Mekacher, Augmented reality (AR) and virtual reality (VR): the future of interactive vocational education and training for people with handicap, PUPIL Int. J. Teaching, Educ. Learn. 3 (2019) 118–129, https://doi.org/10.20319/pijtel.2019.31.118129.

[66] H.F. Moore, M. Gheisari, A review of virtual and mixed reality applications in construction safety literature, Saf. 5 (2019) 51, https://doi.org/10.3390/safety5030051.

[67] R. Schank, Virtual learning : a revolutionary approach to building a highly skilled workforce, McGraw-Hill, New York, 1997.

[68] K.G. Kim, C. Oertel, M. Dobricki, J.K. Olsen, A.E. Coppi, A. Cattaneo, P. Dillenbourg, Using immersive virtual reality to support designing skills in vocational education, Br. J. Educ. Technol. 51 (2020) 2199–2213, https://doi.org/10.1111/bjet.13026.

[69] R. Hämäläinen, B. De Wever, Vocational education approach: new TEL settings—new prospects for teachers' instructional activities? Int. J. Comput. Collab. Learn. 8 (2013) 271–291, https://doi.org/10.1007/s11412-013-9176-1.

[70] J. Tichon, Training cognitive skills in virtual reality: measuring performance, Cyberpsychology Behav. 10 (2006) 286–289, https://doi.org/10.1089/cpb.2006.9957.

[71] M.S. Knowles, The modern practice of adult education : from pedagogy to andragogy , Rev. and U, Association Press, Wilton, Conn, 1980.

[72] M.S. Knowles, E.F. Holton III, R.A. Swanson, The adult learner: The definitive classic in adult education and human resource development, Routledge, 2014.

[73] M.T. Hines III, A day at the SPA (Successful Practices of Andragogy): How to use the ELCC standards and adult learning theory to sustain a "self-as-principal" voice in principal preparation students, AASA J. Scholarsh. Pract. 3 (2006) 44–50.

[74] S. K. Babu, S. Krishna, U. R., R.R. Bhavani, Virtual Reality Learning Environments for Vocational Education: A Comparison Study with Conventional Instructional Media on Knowledge Retention., in: 2018 IEEE 18th Int. Conf. Adv. Learn. Technol., 2018: pp. 385–389. Doi: 10.1109/ICALT.2018.00094.

[75] B. Bhavani, S. Sheshadri, R. Unnikrishnan, Vocational education technology: rural India, Conf Women Comput. India. (2010) 1–7, https://doi.org/10.1145/1858378.1858399.

[76] J.P. Bliss, P.D. Tidwell, The effectiveness of virtual reality for administering spatial navigation training to police officers, Proc. Hum. Factors Ergon. Soc. Annu. Meet. 39 (1995) 936, https://doi.org/10.1177/154193129503901412.

[77] A. Karvouniari, G. Michalos, N. Dimitropoulos, S. Makris, An approach for exoskeleton integration in manufacturing lines using Virtual Reality techniques, Procedia CIRP. 78 (2018) 103–108, https://doi.org/10.1016/j.procir.2018.08.315.

[78] E. Matsas, G.C. Vosniakos, Design of a virtual reality training system for human–robot collaboration in manufacturing tasks, Int. J. Interact. Des. Manuf. 11 (2017) 139–153, https://doi.org/10.1007/s12008-015-0259-2.

[79] J.J. Roldán, E. Crespo, A. Martín-Barrio, E. Peña-Tapia, A. Barrientos, A training system for Industry 4.0 operators in complex assemblies based on virtual reality and process mining, Robot. Comput. Integr. Manuf. 59 (2019) 305–316, https://doi.org/10.1016/j.rcim.2019.05.004.

[80] M. Oberhauser, D. Dreyer, A virtual reality flight simulator for human factors engineering, Cogn. Technol. Work. 19 (2017) 263–277, https://doi.org/10.1007/s10111-017-0421-7.

[81] A. Mehrfard, J. Fotouhi, T. Forster, G. Taylor, D. Fer, D. Nagle, M. Armand, N. Navab, B. Fuerst, On the effectiveness of virtual reality-based training for surgical robot setup, Comput. Methods Biomech. Biomed. Eng. Imaging Vis. (2020), https://doi.org/10.1080/21681163.2020.1835558.

[82] S.I. Scott, T. Dalsgaard, J.V. Jepsen, C. von Buchwald, S.A.W. Andersen, Design and validation of a cross-specialty simulation-based training course in basic robotic surgical skills, Int. J. Med. Robot. Comput. Assist. Surg. 16 (2020) 1–10, https://doi.org/10.1002/rcs.2138.

[83] J. Lucas, W. Thabet, P. Worlikar, A VR-based training program for conveyor belt safety, Electron. J. Inf. Technol. Constr. 13 (2008) 381–417.

[84] M. Jou, J. Wang, Investigation of effects of virtual reality environments on learning performance of technical skills, Comput. Human Behav. 29 (2013) 433–438, https://doi.org/10.1016/j.chb.2012.04.020.

[85] S. Ahn, T. Kim, Y.-J. Park, J.-M. Kim, Improving effectiveness of safety training at construction worksite using 3D BIM simulation, Adv. Civ. Eng. 2020 (2020) 1–12, https://doi.org/10.1155/2020/2473138.

[86] H.-T. Wu, W.-D. Yu, R.-J. Gao, K.-C. Wang, K.-C. Liu, Measuring the Effectiveness of VR Technique for Safety Training of Hazardous Construction Site Scenarios, (2020) 36–39. Doi: 10.1109/ICACEH51803.2020.9366218.

[87] O. Aanuoluwapo, P. Frederick, Virtual Reality Postural Training for Construction, Constr. Res. Congr. 2020. (2021) 565–573. Doi: doi:10.1061/9780784482872.061.

[88] E. Freund, J. Rossmann, T. Hilker, Virtual reality technologies for the realistic simulation of excavators and construction machines: From VR-training simulators to telepresence systems, 2001. Doi: 10.1117/12.417320.
[89] J. Tichon, P. Diver, Interactive Simulator Training in Civil Construction: Evaluation from the Trainer's Perspective, J. Interact. Learn. Res. 23 (2012) 143–163. https://www.learntechlib.org/p/37633.
[90] J.C.Y. So, Reflections on Using a Game Engine to Develop a Virtual Training System for Construction Excavator Operators, 28th Int. Symp. Autom. Robot. Constr. (ISARC 2011). (2011) 631–636. Doi: 10.22260/ISARC2011/0118.
[91] F. Vahdatikhaki, K. El Ammari, A.K. Langroodi, S. Miller, A. Hammad, A. Doree, Beyond data visualization: a context-realistic construction equipment training simulators, Autom. Constr. 106 (2019), 102853, https://doi.org/10.1016/j.autcon.2019.102853.
[92] N. Kayhani, H. Taghaddos, M. Noghabaee, U. (Rick) Hermann, Utilization of Virtual Reality Visualizations on Heavy Mobile Crane Planning for Modular Construction, ISARC. Proc. Int. Symp. Autom. Robot. Constr. 35 (2018) 1–5.
[93] J. Goulding, W. Nadim, P. Petridis, M. Alshawi, Construction industry offsite production: a virtual reality interactive training envifvronment prototype, Adv. Eng. Informatics. 26 (2012) 103–116, https://doi.org/10.1016/j.aei.2011.09f.004.
[94] F. Pour Rahimian, T. Arciszewski, J.S. Goulding, Successful education for AEC professionals: case study of applying immersive game-like virtual reality interfaces, Vis. Eng. 2 (2014) 1–12, https://doi.org/10.1186/2213-7459-2-4.
[95] J.D. Goedert, S. Rokooei, Project-based construction education with simulations in a gaming environment, Int. J. Constr. Educ. Res. 12 (2016) 208–223, https://doi.org/10.1080/15578771.2015.1121936.
[96] C.-Y. Huang, S.-J. Lou, Y.-M. Cheng, C.-C. Chung, Research on teaching a welding implementation course assisted by sustainable virtual reality technology, Sustain 12 (2020), https://doi.org/10.3390/su122310044.
[97] A. Sivanathan, M. Abdel-Wahab, F. Bosche, T. Lim, Towards a Cyber-Physical Gaming System for Training in the Construction and Engineering Industry, (2014). Doi: 10.1115/DETC2014-34930.
[98] J. Kim, S. Ahn, S. Han, Impact of VR settings on immersiveness in VR-based construction skills training: case study of scaffolding work, Constr. Res. Congr. 2020 (2020) 336–344, https://doi.org/10.1061/9780784482865.036.
[99] F. Bosché, M. Abdel-Wahab, L. Carozza, Towards a mixed reality system for construction trade training, J. Comput. Civ. Eng. 30 (2016) 4015016, https://doi.org/10.1061/(ASCE)CP.1943-5487.0000479.
[100] M. Habibnezhad, J. Puckett, M.S. Fardhosseini, L.A. Pratama, A mixed VR and physical framework to evaluate impacts of virtual legs and elevated narrow working space on construction workers' gait pattern, ISARC. Proc. Int. Symp. Autom. Robot. Constr. 36 (2019) 1057–1064, https://doi.org/10.22260/ISARC2019/0141.
[101] O. Golovina, C. Kazanci, J. Teizer, M. König, Using serious games in virtual reality for automated close call and contact collision analysis in construction safety, ISARC. Proc. Int. Symp. Autom. Robot. Constr. 36 (2019) 967–974, https://doi.org/10.22260/ISARC2019/0129.
[102] M. Habibnezhad, S. Shayesteh, H. Jebelli, J. Puckett, T. Stentz, Comparison of ironworker's fall risk assessment systems using an immersive biofeedback simulator, Autom. Constr. 122 (2021), https://doi.org/10.1016/j.autcon.2020.103471.
[103] D. Huang, X. Wang, J. Li, W. Tang, Virtual Reality for Training and Fitness Assessments for Construction Safety, (2020) 172–179. Doi: 10.1109/CW49994.2020.00036.
[104] 3M, Virtual Reality Safety Training, (2020). https://www.3m.com/3M/en_US/worker-health-safety-us/3m-ppe-training/virtual-reality/?utm_medium=redirect&utm_source=vanity-url&utm_campaign=3m.com/safety-vr (accessed April 30, 2021).
[105] Caterpillar, New CAT® Safety VR module creates an immersive safety training experience for employees, (2019). https://www.cat.com/en_US/news/machine-press-releases/new-cat-safety-vr-module-creates-an-immersive-safety-training-experience-for-employees.html (accessed April 30, 2021).
[106] Volvo, Volvo Exc 500 – Excavator Simulator, (2020). https://volvo-ce.oryx.se/product/volvo-exc-500/ (accessed April 30, 2021).
[107] Komatsu, Komatsu Virtual Reality simulators for hire, (2019). https://www.komatsu.com.au/getattachment/5073ce4b-2319-4190-8728-2afdb151b8da/Komatsu-Training-Academy-VR-Simulator (accessed April 30, 2021).
[108] PIXO, VR Training for Construction: Building new realities in 21st Century workforce training, (2020). https://pixovr.com/vr-training-for-construction/ (accessed April 30, 2021).
[109] ST Engineering Antycip, Construction Operator Training, (2020). https://steantycip.com/construction-operator-training/ (accessed April 30, 2021).
[110] Immersive Technologies, Simulators for Komatsu Machines, (2014). https://www.immersivetechnologies.com/products/Komatsu-Training-Simulators.htm (accessed April 30, 2021).
[111] R.S. Haluck, T.M. Krummel, Computers and Virtual Reality for Surgical Education in the 21st Century, Arch. Surg. (Chicago) 135 (2000) (1960) 786–792, https://doi.org/10.1001/archsurg.135.7.786.
[112] C.A. Kilmon, L. Brown, S. Ghosh, A. Mikitiuk, Immersive virtual reality simulations in nursing education, Nurs. Educ. Perspect. 31 (2010) 314–317.
[113] J.L. McGrath, J.M. Taekman, P. Dev, D.R. Danforth, D. Mohan, N. Kman, A. Crichlow, W.F. Bond, R. Fernandez, S. Riker, A.J. Lemheney, T.B. Talbot, D. Franzen, C. Eric McCoy, A. Chipman, K. Parekh, L. Papa, P. Harter, J. Frey, S. Hock, K. Kerrigan, K. Kesawadan, T. Koboldt, M. Kulkornia, P. Mahajan, M. Pusic, D. Robinson, D. Ruby, N.K. Sankaran, J. Siegelman, E. Wang, K. Won, Using virtual reality simulation environments to assess competence for emergency medicine learners, Acad. Emerg. Med. 25 (2018) 186–195, https://doi.org/10.1111/acem.13308.
[114] K.S. Saidi, T. Bock, C. Georgoulas, Robotics in Construction, in: B. Siciliano, O. Khatib (Eds.), Springer Handb. Robot., Springer International Publishing, Cham, 2016: pp. 1493–1520. Doi: 10.1007/978-3-319-32552-1_57.
[115] Occupational Safety and Health Administration (OSHA), Demolition: Construction in Reverse, with Additional Hazards, (2020). https://www.osha.gov/demolition.
[116] Association for Advancing Automation, Demolition Robots Disrupt a Labor-Intensive Industry, A3 Robot. (2020). https://www.automate.org/a3-content/service-robots-demolition (accessed January 15, 2021).
[117] U.S. Bureau of Labor Statistics, 18b. Employed persons by detailed industry and age, (2021). https://www.bls.gov/cps/cpsaat18b.htm (accessed March 1, 2021).
[118] P. Adami, T. Doleck, B. Becerik-Gerber, Y. Copur-Gencturk, L. Soibelman, G. Lucas, An Immersive Virtual Learning Environment for Worker-Robot Collaboration on Construction Sites, in: 2020 Winter Simul. Conf., 2020: pp. 2400–2411. Doi: 10.1109/WSC48552.2020.9383944.
[119] R.B. Johnson, A.J. Onwuegbuzie, L.A. Turner, Toward a definition of fMixed methods research, J. Mix. Methods Res. 1 (2007) 112–133, https://doi.org/10.1177/1558689806298224.
[120] B.G. Glaser, A.L. Strauss, The discovery of grounded theory; strategies for qualitative research, Aldine Pub. Co., Chicago, 1967.
[121] R.B. Johnson, M.W. McGowan, L.A. Turner, Grounded theory in practice: is it inherently a mixed method? Res. Sch. 17 (2010) 65.
[122] J. Saldaña, The coding manual for qualitative researchers, 2nd ed., SAGE, Los Angeles, 2013.
[123] M.B. Miles, A.M. Huberman, Qualitative data analysis: an expanded sourcebook, 2nd ed., Sage Publications, Thousand Oaks, Calif, 1994.
[124] J.R. Landis, G.G. Koch, The measurement of observer agreement for categorical data, Biometrics 33 (1977) 159–174, https://doi.org/10.2307/2529310.
[125] A.G. Abulrub, A.N. Attridge, M.A. Williams, Virtual reality in engineering education: the future of creative learning, EDUCON (2011) 751–757, https://doi.org/10.1109/EDUCON.2011.5773223.
[126] M. Hoffmann, T. Meisen, S. Jeschke, Shifting Virtual Reality Education to the Next Level – Experiencing Remote Laboratories Through Mixed Reality, (2017) 235–249. Doi: 10.1007/978-3-319-46916-4_19.
[127] P.J. Gorman, A.H. Meier, T.M. Krummel, Simulation and virtual reality in surgical education: real or unreal? Arch. Surg. (Chicago) 134 (1999) (1960) 1203–1208, https://doi.org/10.1001/archsurg.134.11.1203.
[128] C.E. Jenson, D.M. Forsyth, Virtual reality simulation: using three-dimensional technology to teach nursing students, Comput. Informatics, Nurs. 30 (2012) 312–318, https://doi.org/10.1097/NXN.0b013e31824af6ae.
[129] B. Esmaeili, S. Bhoir, State-of-the-Art Review of Virtual Reality Environment Applications in Construction Safety, (2015) 457–468. Doi: 10.1061/9780784479070.040.