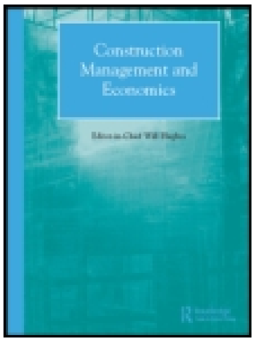

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Construction safety training using immersive virtual reality

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Construction workers' ability to identify and assess risks is acquired through training and experience and is among the key factors that determine their behaviour and thus their safety. Yet researchers have questioned the effectiveness of conventional safety training. This research tested the hypotheses that safety training in a virtual reality (VR) construction site would be feasible and more effective, in terms of workers' learning and recall in identifying and assessing construction safety risks, than would equivalent training using conventional methods. Sixty-six subjects were provided training in construction safety and their safety knowledge was tested prior to the training, immediately afterward, and one month later. Half of the subjects received traditional classroom training with visual aids; the other half were trained using a 3D immersive VR power-wall. Significant advantage was found for VR training for stone cladding work and for cast-in-situ concrete work, but not for general site safety. VR training was more effective in terms of maintaining trainees' attention and concentration. Training with VR was more effective over time, especially in the context of cast-in-situ concrete works. Given the need for improved training and the advantages of training using VR, incorporation of VR in construction safety training is strongly recommended.

Keywords: Construction safety, immersive virtual reality, safety training.

Introduction

Making construction as safe as possible requires concerted effort on the part of all involved: owners, designers, construction companies at all levels of management, construction workers, regulators and educators (Hinze, 1997; Holt, 2001). Construction workers themselves play a major role in determining their own safety through their behaviour, either taking or rejecting risks. Even when a company takes all reasonable precautions in terms of preparing the site and the work, enforcing compliance through disciplinary measures, and providing training and personal protective equipment (PPE), workers can still make decisions to work in ways that endanger them. Their ability to identify risks, and their subjective analysis of the magnitude of those risks, are among the factors that determine their behaviour and thus their safety.

These skills are determined in part by safety training. Training with low engagement (by lectures, videos or demonstrations) which is common in construction, has consistently been shown to be minimally effective when compared with more engaging forms of instruction (Burke *et al*., 2006). Wilkins (2011) suggested that 'there may be a case for delivering less training in an artificial *classroom* environment and more in the workplace, where the practical ramifications of a failure to adhere to safety regulations are more immediately apparent' (p. 1023). Given that one cannot knowingly expose construction workers to hazards, even for purposes of instruction, the research reported here explored the feasibility and the impact of conducting safety training using a virtual construction site presented with a 3D immersive virtual reality power-wall.

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Role and content of training for construction safety

The relatively dangerous nature of the construction industry, as reflected in accident statistics, is well documented. Recent publications that report statistics from around the world include Gangolells *et al.* (2010), Hu *et al.* (2011) and Zhou *et al.* (2012). The loss of life, the costs and the liabilities associated with construction accidents have led through legislation to construction safety programmes, which include training, inspection and enforcement, and this approach appears to have reduced accident rates where it has been applied (Mitropoulos *et al.*, 2005).

Many researchers have used empirical methods to evaluate the effectiveness of training in improving safety. A regression analysis of the safety strategies and the site safety records of 45 Hong Kong construction companies identified safety training as one of the four most effective components of a safety programme (Tam and Fung, 1998). A similar analysis of 70 Thai construction projects found that safety inductions were effective in reducing unsafe conditions (Aksorn and Hadikusumo, 2008). Based on a survey of design and construction firms in Pennsylvania with 105 responses, Toole (2002) identified lack of training as one of eight root causes of construction accidents.

However, standards for construction safety training are low. In the UK, Australia and Hong Kong, one day or less of safety training is sufficient for workers to obtain the necessary certification as construction labourers (Li *et al.*, 2012). Wilkins (2011) raised serious questions concerning the effectiveness and the content of existing modes of construction safety training in the US. His survey of 105 construction personnel who had taken the OSHA 10-hour 'Construction Safety Training Course' revealed dissatisfaction with the ways in which the courses were taught. Wilkins highlighted the needs for training to cover content covered relevant to the lives of the trainees, for presentation by a trainer knowledgeable about the subject, and for supplementing training with tangible materials that are understandable. In the broader domain of safety training in general, a meta-analysis study of research from 1971 to 2003 that compared the effectiveness of safety training methods has shown that high-engagement training (involving behavioural modification, e.g. hands-on practice in a realistic setting) was on average three times as effective as low-engagement training (e.g. using videos or written material only) (Burke *et al.*, 2006). A similar meta-study, covering the years 1996–2005, also found (inter alia) evidence for the superiority of high-engagement over low-engagement training, although the difference was small (Robson *et al.*, 2010).

One of the assumptions of the 'safety programme' approach is that a worker's role in an accident can be thought of as that of a link in a chain of causation, as typified by accident causation models like the classical 'domino theory' (Heinrich, 1936). In this view, training workers to identify hazards, and thereby avoid or prevent them, is one of the defences that can help break the chain. Abdelhamid and Everett (2000) found that lack of awareness of hazards on the part of construction workers was a significant contributing factor to the occurrence of accidents. Mitropoulos *et al.* (2005) convincingly argue, however, that the 'safety programme' approach has a limited view of accident causality 'as it ignores the work system factors and their interactions that generate the hazardous situations and shape the work behaviours' (p. 816). They maintain that the uncertainty that is typical of construction, coupled with the unstructured nature of work tasks and interactions between crews, leads to unpredictable work conditions that contribute to accident causation. In this view, two additional actions are needed to increase safety: increase the reliability of production planning and improve error management capabilities. The latter refers to increasing workers' ability to avoid hazards and mitigate errors, which can be enhanced by training workers to recognize hazards through situational awareness, rather than through training workers in prescriptive performance of standardized work procedures.

Hazards that arise on construction sites may be either predictable, as part of planned activities, or emergent (i.e. arising in dynamic ways and resulting in unpredictable situations). Cognitive and psychomotor processes including decision-making capacity, attention, reaction time, contrast sensitivity, and visual pursuit are integral aspects of hazard perception skills (Horswill *et al.*, 2008; Sümer, 2011). Accordingly, hazard perception is a multi-component cognitive skill and this skill can improve with experience (Deery, 1999). Training can improve a person's ability to diagnose the potential hazard and risk correctly (Duffy, 2003) and experience can have a positive impact on risk-taking perception and behaviours particularly in the perception of the risk of injury (Knight *et al.*, 2012).

In his seminal work defining the 'perceived boundary of acceptable performance' model of worker behaviour in relation to safety, Rasmussen (1997, p. 183) stated that:

> In spite of a widely used 'defence-in-depth' design strategy, most recent major accidents in large scale

> industrial systems appear to be caused by operation of the systems outside the predicted preconditions for safe operation during critical periods with excessive pressure from a competitive environment.

The model explains the opposing pressures on workers. The dual pressures to increase productivity while investing minimal personal effort are countered by the restraining pressure from 'campaigns for safety culture'. Safety training is central to the safety culture. According to this model, improving the effectiveness of training will contribute to inducing safety conscious behaviour because the perceived boundary of acceptable performance will lie within the boundary of functionally safe performance.

For all of these reasons, the investigation of safety training reported here focuses on improving the ability of construction personnel to identify and respond to hazards, rather than on prescriptive instruction of standardized methods to perform specific tasks.

Safety training with virtual reality

Virtual reality (VR) is a technology that uses computers, software and peripheral hardware to generate a simulated environment for its user. The environment may simulate a real or an imaginary environment. An *immersive virtual environment* (IVE) is a computer-generated environment that gives a person a sense of being within it by engaging the person's senses and reducing or removing their perception of the real environment. While there is a wide range of technical implementations, an IVE will typically have the following features: it will surround its user, obscuring cues from the physical environment and increasing the sense of 'presence' within the IVE; provide a three-dimensional visual representation of the virtual environment; track the user's location and orientation and update the virtual scene to match the user's movements; and give the user some degree of control over the objects in it (Bailenson *et al.*, 2008). A central notion is that of 'presence' in the virtual environment, i.e., that subjects' responses in the virtual environment are similar to their responses in a real environment (Sanchez-Vives and Slater, 2005).

The use of VR in training workers of various kinds is common. Flight simulators are a well-known example and VR has been shown to be effective for road-safety training (Thomson *et al.*, 2005). VR training simulations for surgical procedures are common because they avoid the danger inherent in training on humans or animals (Sutherland *et al.*, 2006).

The hazardous nature of construction sites in and of itself makes onsite training difficult, and certainly prevents training through experience of failure. One solution is to construct purpose-built training facilities that physically simulate the construction site (de Vries *et al.*, 2004); such facilities exist in the Netherlands, the UK and in Australia. VR systems and IVE offer the opportunity to expose workers to hazardous situations, and indeed to accidents, as part of training. Workers can assess a situation, decide on a course of action, implement the action and immediately observe the results. This results in cognitive information processing, which leaves its mark in long-term memory (Lucas *et al.*, 2008).

Lucas *et al.*'s (2008) research in safety training for operators of construction equipment is one of the very few examples of the use of VR for construction safety training. Another example is a generic industrial safety VR training game, developed for the California State Compensation Insurance Fund, which contains a module that simulates material handling for construction of a timber roof on a house (ForgeFX, 2012). Ku and Mahabaleshwarkar proposed the possibility of construction safety training using 'Second Life', highlighting numerous challenges (Ku and Mahabaleshwarkar, 2011). Li *et al.* (2012) used a 3D game engine to generate a 'virtual safety assessment system' (VSAS) which uses VR scenes projected on a PC to assess construction workers' competence with regard to safety.

As can be seen by the dearth of examples, the use of immersive virtual reality for training interventions in construction to date is rare and the knowledge about their use and effectiveness is severely limited. Some of the practical challenges for researchers have been the significant investment required to prepare the immersive VR content, including 3D scenery, animations and the pedagogical aspects, and the need to bring workers to a fixed facility.

Aims and objectives

Despite the importance of training as a component of safety programmes, the construction industry around the world has yet to adopt a sufficiently sophisticated approach. The criticisms of traditional modes of training, summarized in part in the literature review above, have led various researchers to propose, and some to test, the use of VR simulations for safety training. Yet there is still much to be learned, both because the effectiveness of IVE systems for construction has not been tested rigorously and because the successful use of IVE or VR safety training systems in other industries cannot prove their effectiveness in the construction industry.

Therefore, we sought in this work to build a virtual construction site using IVE technology, to compile a set of safety training scenarios, and to test the setup using a set of experiments with a between-group design. The first hypothesis was that trainees would perceive the virtual construction site environment to be a sufficiently authentic simulation of a construction site to facilitate learning. The second hypothesis was that safety training in the virtual construction site would be more effective, in terms of workers' attention, learning and recall, and their ultimate success in identifying and assessing construction safety risks, than would training using conventional methods. The latter essentially tests Burke *et al.* (2006)'s conclusions concerning 'high-engagement' versus 'low-engagement' training in the construction context. An additional specific goal was to gain practical knowledge about the virtual construction site and its use: to learn from the implementation and from the conduct of the training sessions.

Method

The research compared safety training using conventional methods vs. training, using immersive virtual reality with a 'between-participant' experimental design. The experimental setup exploited the controllable nature of virtual environments to allow study of training interventions within a complex and realistic environment. We adopted a behavioural experiment research approach rather than using survey or other methods because experiments can better determine cause-and-effect relationships (Campbell *et al.*, 1963). Three groups of 20 to 25 subjects each took part in three replications of the experiment (an earlier pilot experiment was performed with five subjects). The procedure consisted of five steps:

(1) An individual safety knowledge test, to set the baseline for measurement. The test scope and technique is described in detail below.
(2) Safety training: at this stage each group was randomly divided into two sub-groups of 10–12 subjects each. Each sub-group received two hours of training on the same construction safety topics, but one sub-group received conventional classroom instruction supported with slides (photos, graphics and text), while the other sub-group received the same instruction in a virtual construction site.
(3) A second individual safety knowledge test was applied immediately after training, using the same test instrument.
(4) Subjects were asked to fill out an individual experience questionnaire immediately after the second safety test.
(5) A third safety knowledge test was given approximately one month after training in order to measure the subjects' degree of recall. This test is called the 'short-term' test, in accordance with the definitions provided by Robson *et al.* (2010, p. 19). Once again, the same instrument was used.

In the research design, a number of steps were taken to maximize reliability and validity: the groups were divided randomly; a full-scale pilot experiment was conducted to test the equipment and prepare the experimenters; the experiment was repeated three times; the subjects were tested for their baseline safety knowledge before starting the experiments; and the pre-experiment baseline results were compared across the randomly divided sub-groups to confirm that there was no significant difference in their initial safety knowledge and risk perception skills. In the latter case, a T-test comparison was made for risk perception, prevention and risk evaluation results for each of the three training topics. All nine results were well outside the 10% limit of significance (six approached the maximum 50% result for perfectly matched populations), indicating that the groups could not be distinguished from one another.

Population

A total of 71 subjects took part in this experiment in four distinct groups, as shown in Table 1. After the initial pilot phase, which served for testing and refining the method, three groups with a total of 66 subjects were tested. Groups 1 and 3 were comprised of construction workers from a cast-in-situ concrete vocation training course. These subjects had limited work experience, but they were familiar with construction site environments. Group 2 was composed of third year BSc civil engineering students. These subjects also had limited work experience, and in this group, most had little or no prior experience of the construction site environment.

Immersive virtual environment

The virtual site consisted of a construction site simulation displayed on an immersive virtual reality power-wall. The power-wall setup consisted of three rear-projection screens, each 2.4m wide and 1.8m high, arranged in a 'theatre' with a 150° angle

Table 1 Experiment population

Group	Description	Number of subjects in training sessions	Number of completed competence tests one month after training
Pilot	4th year BSC students, Faculty of Civil Engineering	5	–
1	Cast-in-situ concrete worker trainees (near the end of their three-month course at the time)	20	2
2	3rd year BSc students, Faculty of Civil Engineering	25	15
3	Cast-in-situ concrete worker trainees (one month into their three month course)	21	6
	Totals for groups 1 to 3	66	23

Figure 1 Immersive VR power-wall setup in the virtual construction laboratory

between each screen, as shown in Figure 1. This is an open configuration of a three-sided EON ICube CAVE (Cave Automatic Virtual Environment) that uses 3D stereo projection with active glasses that have a 120Hz frequency. The VR stereo software projection system was EON Studio V7.0. The instructor, and in turns each of the trainees, used a head tracking system and an XBOX controller that was also tracked using eight cameras mounted on the tops of the screens. Black curtains above the screens hid the ceiling space beyond them and the 3D projectors were the only source of light. The setup also has a stereo sound system.

This setup fulfils many but not all of the conditions for an 'ideal' IVE as outlined by Bailenson *et al.* (2008) and others; it does not entirely exclude the perception of the physical environment for all of the users, and at any given time only the user wearing the tracked glasses was at the vantage point of an actor in the environment (the others were restricted to the sense of accompanying him or her, having no control of their own movement).

Training materials

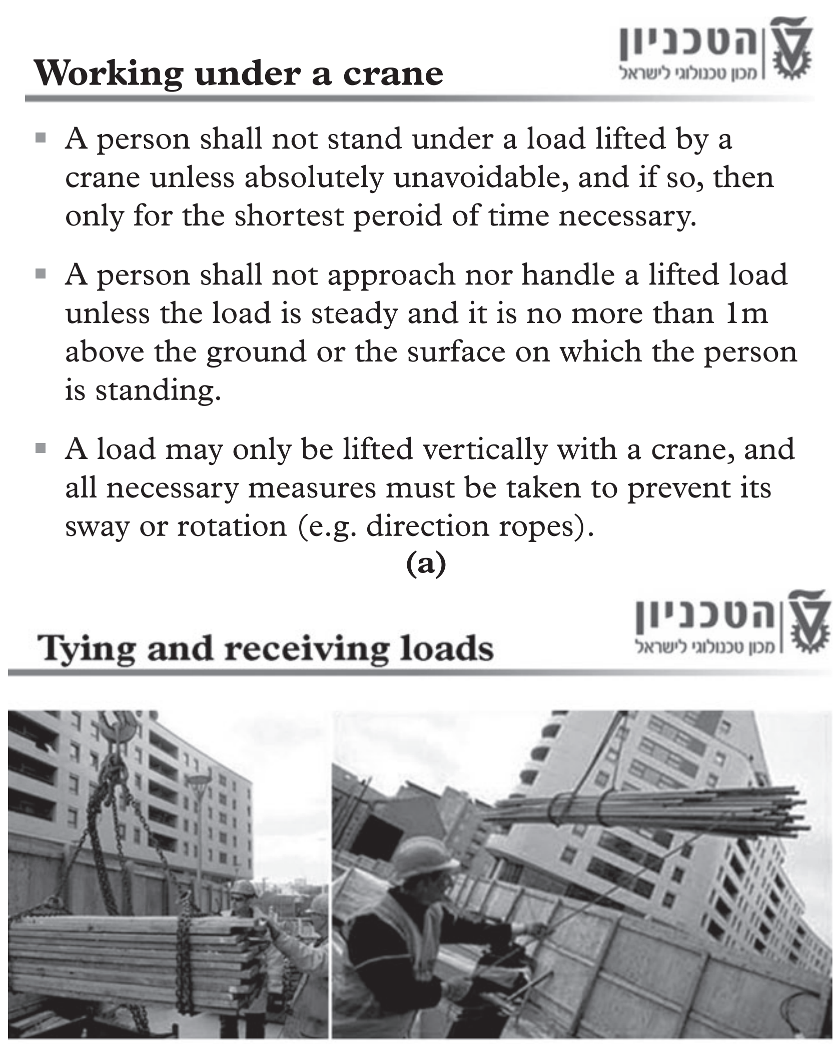
The content for the training was selected based on the frequency of accident types reported in Perlman *et al.* (2012) as a guide. Within the more common accident types, specific hazards were selected according to their relevance to the local population of construction workers, and their amenity to visualization. The topics were organized in three chapters:

(1) General site safety, including vehicle and worker movement on site, working under cranes, falls from heights and personal protective equipment (PPE).
(2) Safety in cast-in-situ concrete, including work at heights, working with tools and equipment (steel formwork, concrete pumps, reinforcement).
(3) Safety during stone cladding work on facades, including work on scaffolding, working with electrical tools and winches.

A half-hour lesson plan was prepared for each chapter. The materials were collated from safety codes and from the standard construction supervisors' safety courses run by the Israel Institute for Occupational Safety and Hygiene (IIOSH). Visual material was supplemented with numerous photographs taken at three construction sites. A set of presentation slides was prepared for each chapter (examples are shown in Figure 2(a) and (b)). Once the presentations for the classroom training were ready, the work of preparing equivalent content for the virtual reality environment began. The textual and theoretical slides were unchanged; but all of the visual material was replaced with VR scenarios, each with various possible safe and unsafe starting situations and outcomes.

A detailed storyboard was prepared for each of the 21 VR scenarios. Figure 3 shows a typical example. In this case, workers are tying reinforcement to form a column cage. As can be seen in the photograph, they are using two formwork shutter pieces as a temporary work surface and face the danger of the shutters falling on to them. Each storyboard included full details of the mechanism of the accident scenario that it described: which objects move, their motion paths, rotation axes, what other objects they affect, etc.

All 21 scenarios were implemented within a virtual construction site which was composed and tested in earlier work (Perlman *et al.*, 2012). The site incorporated a residential building under construction with an entrance floor with a tall lobby space, four apartments on each floor, elevator shafts and stairwells. Figure 4 shows the entrance of the building and part of the site. Cast-in-place concrete works were underway on its eighth floor, interior and finishing works



(b)

Figure 2 Examples of slides from the general site safety chapter: (a) text instructions and (b) an illustration of the correct way to receive a load

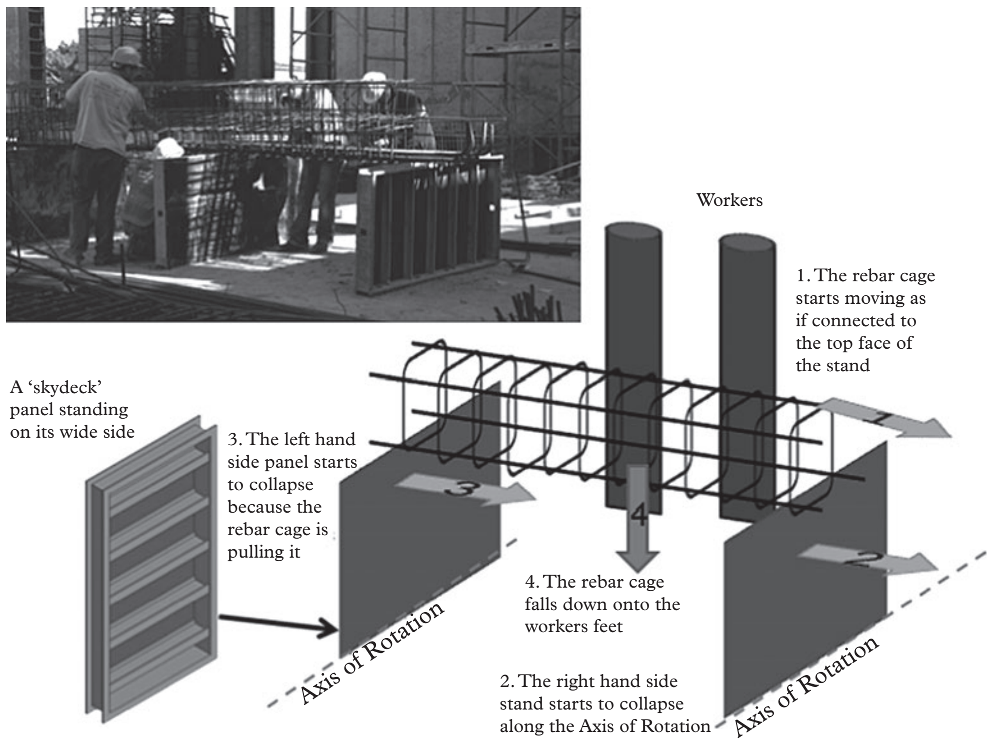


Figure 3 Storyboard example for reinforcement working table collapsing

Figure 4 A partial view of the virtual building under construction

were being performed in apartments on the third and fourth floors, and stone cladding work was being done on the facades. A work elevator, tower crane, concrete pump and a variety of earthworks equipment and trucks were modelled operating on the site. Static equipment (scaffolding, formwork, shoring, various interior work platforms, hand tools, reinforcing cages and starter bars), materials (palettes of blocks, bags of cement, floor tiling packages, etc.) and waste and refuse were included to enhance the effect. Background sounds of a construction site were used for the audio track, together with the sounds of the vehicles travelling.

Three software tools were used. The building itself was modelled in REVIT; all other 3D geometry was modelled using 3D Studio MAX, and the VR scenarios were generated with EON Studio v6. The movements of objects in the scenarios were implemented in two ways: (1) 'physics' animation, in which objects behave as rigid objects subject to the force of gravity and move accordingly; and (2) 'keyframe' animation, in which objects move along predefined paths. Physics animation was used wherever possible, but in some circumstances the inability of the physics engine to deform objects under impacts generates highly unrealistic behaviour, resulting in the need to carefully programme object motion paths.

The requirement for training of groups led to selection of a 'third person' view, in which the camera was positioned so that all of the subjects see an avatar who is the accident victim. An alternative configuration uses a 'first person' view, in which the subject is the victim, experiencing, for example, his or her own fall. This option is suitable for a single trainee, but not for groups. The default views for each scenario were therefore positioned to make the scene tangible and enhanced the experience of danger. Of course, using the controller, the trainer was able to navigate to any alternative point of view and to repeat the virtual accident as needed.

Safety test

A safety knowledge test was applied to each subject immediately before the training, immediately after the training, and again one month later. The third test was applied remotely, with the result that it was not possible to maintain full participation. Of the 52 subjects who began the third test, 23 completed it.

The same test was used at all three testing steps. The correct answers were not revealed at any point. The test had three chapters, one for each training topic: general site safety, cast-in-situ concrete work and stone cladding work. Each chapter had three question types:

(1) Open questions, where the subject had to identify different potential hazards apparent in a set of photographs from construction sites, recommend ways to eliminate them, and assess their risk level (on a scale of 1 to 5).
(2) Behaviour questions, where subjects were presented with an image of a construction scene with a specific hazard and asked how they would behave in the situation depicted: (a) work as usual; (b) inform the foreman and continue working as usual; (c) fix the hazardous situation themselves; or (d) refuse to work in that situation.
(3) Knowledge questions, where the subjects had to identify appropriate safety equipment, safety instructions and terminology.

To score the open question, responses of all of the subjects were scanned and a list of all the hazards identified was composed. Individual scores were then computed by evaluating what proportion of the full list of hazards each subject had identified. Both the total number of identifications and the number of unique identifications were used (in many cases, subjects identified the same hazard more than once in their responses). Similarly, the score for eliminating hazards was the number of unique and correct methods identified for eliminating each hazard. To score the risk level assessments, a panel of three IIOSH construction safety instructors was asked to set a normative value for each hazard's probability, severity and risk level. The score for risk level for each subject was computed as the standard deviation of the set of the absolute differences between the subject's answers and the safety experts' answers.

Training experience questionnaire

Immediately after the training, the subjects were asked to complete a questionnaire to assess their experience. The questionnaire included questions about knowledge, emotions and attitudes. The goal was to compare the experience of subjects in the VR training with that of those who had the traditional training. The questions posed are detailed in Table 5 below together with the results.

Results

The safety test scores were compared in three different ways, to determine immediate effectiveness of the training, short-term effectiveness, and the degree of recall. The results of the learning experience questionnaire were used to triangulate the three safety test score comparisons and to reveal other aspects of the training's effect on the subjects.

The first set of results compares the subjects' safety test scores from the tests taken just prior to the training with the scores from the tests taken immediately after the training. The differences between the 'before' and 'after' scores were computed and the significance of the difference between the two populations was evaluated using T-tests. The degree of significance (95%, 90% or none) is noted in the penultimate column of Table 2.

The results demonstrate effectiveness in immediate learning of hazard identification and prevention skills for both the VR and the traditional training groups (Table 2). Over all three of the safety training topics, the differences between before and after scores for risk identification ($t = -5.77$, $p < 0.05$) and prevention ($t = -4.92$, $p < 0.05$) were significant. Within the topics, significant differences were found for the

Table 2 Safety testing data to examine immediate effectiveness (n = 66)

Skill	Traditional groups test results		Virtual reality groups test results		Training effect (sig.)	Advantage of VR (sig.)
	Before	After	Before	After		
Total over all safety training chapters						
Identification	9.77	11.17	9.67	13.08	**	**
Prevention	6.47	7.57	7.69	11.06	**	**
Risk level assessment	1.55	1.98	2.11	1.83	NS	NS
General site safety						
Identification	4.03	4.93	3.86	4.89	**	NS
Prevention	2.80	3.23	3.06	4.17	**	NS
Risk level assessment	0.64	0.72	0.73	0.67	NS	NS
Reinforced concrete works						
Identification	1.80	1.60	1.86	2.58	*	*
Prevention	1.33	0.97	1.75	2.44	NS	**
Risk level assessment	0.52	0.68	0.70	0.63	NS	**
Stone cladding works						
Identification	3.93	4.63	3.94	5.61	**	**
Prevention	2.33	3.37	2.89	4.44	**	NS
Risk level assessment	0.52	0.54	0.63	0.53	NS	NS

Notes: Safety tests applied before training and immediately after training. T-test results: ** $p < 0.05$, * $p < 0.1$, NS = no significance.

topics 'general site safety' in risk identification scores ($t = -4.1$, $p < 0.05$) and in prevention scores ($t = -2.74$, $p < 0.05$); similarly, for 'reinforced concrete works' significant differences between before and after scores were found for risk identification ($t = -1.76$, $p < 0.1$); for 'stone cladding works', significant differences between before and after scores were also found for risk identification ($t = -4.42$, $p < 0.05$) and prevention ($t = -5.56$, $p < 0.05$). Interestingly, those who had the traditional training rated the risk levels higher after the training; the VR training groups, on the other hand, reduced their risk level assessments after training.

The results were also used to assess any possible advantage of VR over traditional training. For this, the margin of improvement of the test scores for each type of training was compared. Here, the results were different for the different sub-topics of the safety training. VR was significantly better than traditional training for hazard identification for reinforced concrete works ($t = 1.08$, $p < 0.1$) and for stone cladding works ($t = 1.76$, $p < 0.05$); it was also significantly better for learning prevention knowledge for the cast-in-situ concrete works ($t = 3.29$, $p < 0.05$). Although the results indicate an advantage for the general site safety topic as well, this cannot be asserted with confidence.

Short-term effectiveness of the training was investigated by comparing scores for the safety tests administered before training and one month after training (see results in Table 3). In all cases, scores on identification task and on the prevention task were significantly improved after training. In particular we found training to be effective in scores on risk identification for reinforced concrete works ($t = -2.57$, $p < 0.05$) and stone cladding works ($t = 2.28$, $p < 0.1$), and in scores for prevention for general site safety ($t = -3.85$, $p < 0.1$) and stone cladding works ($t = 1.76$, $p < 0.05$). Due in part to the small sample size, it was not possible to establish a clear-cut advantage for the virtual reality training, with the exception of cast-in-situ concrete works, where the superiority of the VR training proved to be statistically significant for scores on identification task ($t = 2.58$, $p < 0.05$) and on the prevention task ($t = 1.85$, $p < 0.05$).

We also investigated recall after training by comparing scores after training to scores one month later (see results in Table 4). In most cases the differences between the two times were not significant, indicating that recall was good. However we did find some differences in scores for risk identification for general site safety ($t = 2.19$, $p < 0.1$) and stone cladding works ($t = 3.14$, $p < 0.05$) and for prevention for general site safety ($t = 2.18$, $p < 0.1$) and stone cladding works ($t = 4.40$, $p < 0.05$). However, with the exception of risk level assessment for stone cladding works ($t = 2.42$, $p < 0.05$), we could not demonstrate significant differences between VR and traditional training.

Finally, participants were all asked to complete a questionnaire in which they evaluated various aspects

Table 3 Safety testing data to examine the short-term training effectiveness (n = 23)

	Traditional groups test results		Virtual reality groups test results			
Skill	Before	After one month	Before	After one month	Training effect (sig.)	Advantage of VR (sig.)
Total over all safety training chapters						
Identification	7.50	8.67	8.88	11.06	**	NS
Prevention	5.50	6.17	9.59	11.06	*	NS
Risk level assessment	1.57	1.86	2.10	1.68	NS	NS
General site safety						
Identification	3.17	3.50	3.53	4.18	NS	NS
Prevention	2.50	2.50	3.88	4.06	*	NS
Risk level assessment	0.52	0.90	0.88	0.55	NS	NS
Reinforced concrete works						
Identification	1.67	1.67	2.06	3.00	**	**
Prevention	1.33	1.00	2.35	2.24	NS	**
Risk level assessment	0.66	0.67	0.58	0.44	NS	NS
Stone cladding works						
Identification	2.67	3.50	3.29	3.88	*	NS
Prevention	1.67	2.67	3.35	3.76	**	NS
Risk level assessment	0.93	0.29	0.64	0.69	NS	NS

Notes: Safety tests applied before training and one month after training. T-test results: ** $p < 0.05$, * $p < 0.1$, NS = no significance.

Table 4 Safety testing data to examine recall (n = 23)

	Traditional groups test results		Virtual reality groups test results			
Skill	After	After one month	After	After one month	Recall effect (sig.)	Advantage of VR (sig.)
Total over all safety training chapters						
Identification	10.00	8.67	13.35	11.06	*	NS
Prevention	10.00	6.17	13.47	11.06	*	NS
Risk level assessment	2.15	1.86	1.61	1.68	NS	NS
General site safety						
Identification	4.33	3.50	5.12	4.18	*	NS
Prevention	4.17	2.50	5.12	4.06	*	NS
Risk level assessment	0.62	0.90	0.65	0.55	NS	NS
Reinforced concrete works						
Identification	1.17	1.67	2.88	3.00	NS	NS
Prevention	1.33	1.00	3.00	3.24	NS	NS
Risk level assessment	0.84	0.67	0.48	0.44	NS	NS
Stone cladding works						
Identification	4.50	3.50	5.35	3.88	**	NS
Prevention	4.50	2.67	5.35	3.76	**	NS
Risk level assessment	0.66	0.29	0.49	0.69	NS	**

Notes: Safety tests applied immediately after training and one month after training. T-test results: ** $p < 0.05$, * $p < 0.1$, NS = no significance.

of the learning experience. The results are shown in Table 5. Here we found a significant advantage for VR over traditional training ($t = -5.65$, $p < 0.05$) for a variety of parameters. The advantages of VR were measured in question 2 ('To what extent was your feeling strong that the demonstrations represent real situations in construction sites?') and question 6 ('During the training, did you feel discomfort due to

Table 5 Results of the learning experience questionnaire (n = 66)

Question	Traditional (n = 31)	VR (n = 35)	T-test significance
1. Did you feel that the dangers were demonstrated realistically?	4.0	4.0	NS
2. To what extent was your feeling strong that the demonstrations represent real situations in construction sites?	3.8	4.2	*
3. How strongly will the training affect your learning about safety?	3.8	4.2	**
4. To what extent will you remember what you've learned a year from now?	3.4	3.8	*
5. To what extent will training affect your behaviour on a construction site?	3.8	4.4	**
6. During the training, did you feel discomfort due to the thought of a possible accident at work?	3.2	3.6	*
7. Could the training illustrate realistic situations in the field?	3.9	4.0	NS
8. Did you feel you were concentrating in class?	3.4	4.2	**
9. To what extent was the learning a pleasant experience?	3.7	4.2	**
10. Will you recommend similar training to your friends?	3.6	4.2	**
11. Do you want to have similar training in the future?	3.8	4.2	*
12. Will the training help you avoid accidents on the site?	4.1	4.5	**
13. To what extent was the time of the training a worthwhile investment?	4.1	4.5	**
14. Overall, was the training a pleasant learning experience?	4.1	4.6	**
15. Will the training influence your attitudes to safety?	4.3	4.5	*
16. Rate the quality of training on general site safety.	4.2	4.4	*
17. Rate the quality of training on safety in reinforced concrete works.	4.2	4.2	NS
18. Rate the quality of training on safety in stone cladding works.	4.3	4.3	NS
19. During the training, what was the strength of feeling of discomfort from each of the following potential accidents:			
a. Man falling from the scaffold to the ground	4.0	4.0	NS
b. Injury to a worker from exposed reinforcing bars	3.3	3.8	*
c. Run over by a truck	3.5	3.5	NS
d. Scaffolding collapse on people	3.7	3.8	NS
e. Worker crushed by a concrete beam lifted by a crane	3.5	3.9	NS
f. Worker crushed by steel shuttering/formwork for concrete	3.7	3.7	NS
g. Worker injured by falling objects	3.8	3.6	NS
All	3.7	4.0	**

Notes: Scores range from 1 = 'not at all' to 5 = 'very much' or 'very strongly'. T-test results: ** $p < 0.05$, * $p < 0.1$, NS = no significance.

the thought of a possible accident at work?'). Both had significant results ($\Delta = 0.4$, $p = 0.084$ and $\Delta = 0.4$, $p = 0.096$ respectively).

The results also appear to reflect an observation made during the training concerning the degrees of attention and concentration of the trainees. The researcher who observed the traditional training sessions noted that trainees tended to lose concentration after about 40 minutes; they asked to leave the room to freshen up, they began to use their mobile phones, and their attention was diverted from the material. The instructors allowed them a break. In contrast, the virtual reality trainees were observed to maintain full focus for the hour and a half of the training session. The results for question 8 ('Did you feel you were concentrating in class?'; $\Delta = 0.8$, $p = 0.0002$) and question 9 ('To what extent was the learning a pleasant experience?'; $\Delta = 0.5$, $p = 0.01$) show this difference. While these results do not necessarily reflect or measure the sense of presence as discussed above, they are in line with the literature; for example, tests have shown that children more easily pay attention in a virtual classroom environment and that VR is effective in sustaining one's attention (Cho *et al.*, 2002).

Discussion and conclusions

This research has shown that it is possible to build a virtual construction site using IVE technology that incorporates safety scenarios and that it can be used effectively for training. The first hypothesis, that trainees would perceive the virtual construction site environment to be a sufficiently authentic simulation of a construction site to facilitate learning, is supported both by the VR learning outcomes and by the responses to the post-experiment evaluations. In general, we found that instruction using virtual reality was more effective than safety training with traditional classroom training methods using slide presentations, thus confirming the second hypothesis.

Virtual reality training was the more effective learning experience. Specifically, we found a distinct advantage for virtual reality training for stone cladding work and for cast-in-situ concrete work. We did not find a clear advantage for site safety in general. Trainees maintained a high level of alertness for the entire period in the virtual reality training. By contrast, in normal training, trainees were unable to maintain concentration beyond the first hour. Finally, training with virtual reality was more effective over time than traditional training, especially in cast-in-situ concrete works. It was not possible to determine unambiguously the advantage of learning effectiveness of VR in the long run for the other types of work. Those trained with traditional lessons rated risk levels higher after training, whereas those trained with VR lowered their risk assessments. These results are consistent with Burke *et al.*'s (2006) findings that the higher the level of engagement in safety training, the more effective it is. Given the average age of the trainee subjects (almost all in their early 20s), the benefit of computerized learning for people accustomed to computerized environments identified by Font (2004) may also explain some of the advantages.

Although subjects rated the VR scenarios highly in terms of the realism of their depiction of situations in construction sites, the advantages of the VR training may have been underestimated. This is because the VR scenarios built for the experiments were limited in their degree of sophistication and reality. Preparation of VR scenarios is an intensely time-consuming task, requiring attention to fine details and with a steep learning curve. Therefore, whereas the traditional training was based on mature materials, in a commercial setting the VR training materials could likely be improved significantly beyond the level achieved. This may have increased the likelihood of identifying significant differences between the two approaches.

A basic conflict found in the course of the research is the apparent need to reduce the degree of intensity of the learning experience as the size of the trainee group increases. Maximum effect is obtained for an individual in immersive 3D when he or she experiences the 'virtual' hazard first hand, i.e. when they are navigating the model themselves. However, with groups of trainees (10–12 in each group in this case), time constraints for training prevent use of the controller for each scenario by each and every trainee. The nature of the virtual reality scenarios themselves is dependent on the degree to which the trainees will be observers rather than direct participants. With fewer participants, individual subjects can be given more opportunities to control the environment, thus maximizing the effectiveness of the learning (Bailenson *et al.*, 2008). Further research is needed to find the correct balance between the degree of first hand control that is needed, on the one hand, and the ability to train large groups of construction workers.

The results and their discussion highlight important advantages of virtual reality environments for construction safety training. First, VR has been shown to be suitable for presenting trainees with hazards directly and realistically without compromising their safety. Second, the research has shown that safety training with VR holds the attention of trainees better than conventional classroom training does. Thirdly, VR can be used to give trainees a measure of control over the environment, thus reinforcing learning. The primary disadvantage lies in the cost of developing training materials and virtual construction sites.

Against the background of the dissatisfaction with existing modes of training expressed by Li *et al.* (2012) and Wilkins (2011), among others, there is a clear need for improved training for construction safety. The results of this research have shown that the use of training that incorporates VR is feasible and has distinct advantages over traditional methods. Its use with other interactive methods is therefore strongly recommended.

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