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Hazard recognition and risk perception in construction

Amotz Perlman [a,b], Rafael Sacks [a,*], Ronen Barak [a]

[a] Virtual Construction Laboratory, National Building Research Institute, Technion – Israel Institute of Technology, Israel
[b] Department of Management, Bar-Ilan University, Israel

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ABSTRACT

A construction superintendent's ability to recognize hazards and to perceive and assess risk is an essential skill for maintaining safe conditions on their construction sites. In a study that aimed to explore the degree to which construction superintendents are aware of hazards and how well they perceive the associated risks, 61 subjects were asked to identify the hazards in a typical construction project, to assess their risk level, and to estimate the probability and the severity of possible accidents. Some subjects were presented with photographs and construction documents, while others toured a virtual construction site using a 3-sided virtual reality CAVE. The method allowed both for analysis of differences in perception and assessment between distinct populations and for evaluation of the effectiveness of the virtual environment in demonstrating hazardous situations. Results show that construction superintendents with many years of experience are unable to identify all of the hazards in their work environment, and that there are important discrepancies between the way they assess risk levels and the way most formal safety risk assessment methods rate risk levels. Most subjects in the virtual environment assessed higher risk levels to hazards caused by moving equipment. They also identified more hazards correctly than the subjects who studied photographs and documents. Of primary concern is the apparent lack of correlation between hours of safety training and work experience on the one hand, and hazard identification and perception skills on the other hand.

1. Introduction

Most textbooks and guidelines on construction safety list hazard identification and risk assessment as the first steps in safety risk management (e.g., Covan, 1995; Hinze, 1997; HSE, 2011). Yet construction superintendents have difficulty identifying hazards (Sacks et al., 2009). Carter and Smith (2006) found that only 6.7% of method statements in UK construction sites identified all of the relevant hazards. Research in construction operations has shown that familiarity with a task can in fact lead to decreased perception of a hazard, such as painters being 'desensitized' to the risks associated with working on ladders (Zimolong and Elke, 2006).

Furthermore, construction personnel often function in unplanned conditions due to disruption of their regular work. Using an ecological momentary assessment (EMA) method, Menches and Chen (2012) found a high rate of disruptions and that all of the disruptions to a worker's activity required improvisation. Human error is one of the key reasons for construction industry accidents (Saurin et al., 2004). Errors can stem from carelessness or lack of awareness on the part of workers (Abdelhamid and Everett, 2000). According to Rasmussen's model, workers' motivation to achieve high levels of productivity pushes them to work 'near the edge' in terms of their exposure to hazards (i.e. beyond the zone of control or recovery) (Mitropoulos et al., 2005).

In this dynamic work environment, the role of the construction superintendents, who in most countries are responsible for the physical conditions on site, is crucial. They are directly in charge of construction operations and their management on a daily basis. It is the superintendents' duty to organize labour, material, equipment and subcontractors (e.g., Gunderson and Gloeckner, 2011). The role of the foreman or the superintendent has been identified, both by managers and workers, as one of the most powerful influences on the safe work behaviours of workers (Gillen et al., 2004a,b). Sawacha et al. (1999) concluded that operatives "see their superintendent's attitude towards safety as being a major source of influence upon their behavior on site."

Accordingly, improving construction superintendents' hazard recognition and risk perception abilities should improve safety at the site. Numerous studies have shown that hazard recognition and risk perception of workers and drivers can be improved by training intervention. For example, Rethi et al. (1999) prepared a hazard recognition training program with visually degraded stimuli for construction and maintenance activities on mines. The

* Corresponding author. Address: Room 840, Rabin Building, Faculty of Civil and Env. Eng., Technion – Israel Institute of Technology, Technion Campus, Haifa 32000, Israel. Tel.: +972 4 8293190; fax: +972 4 8324534.
E-mail address: cvsacks@techunix.technion.ac.il (R. Sacks).

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training improved the hazard recognition skills of miners (Kowalski-Trakofler and Barrett, 2003) and training that included simulation exercises and used three dimensional slides improved workers' ability to recognize roof hazards (Barrett and Kowalski, 1995). Participants who received video-based road commentary training detected and identified substantially more hazards than control groups, showing that road commentary training seems to be effective (Isler et al., 2009). Additionally, instruction of novice drivers about the deficiencies in their visual search skills or strategies was shown to have positive influence on visual search patterns (Chapman et al., 2002).

The aim of this research was to explore the extent to which construction superintendents perceive hazards and how they assess risk. The first hypothesis to be tested (H1) was that their ability to identify hazards and correctly assess risks should exhibit positive correlation with the extent of their work experience and of their formal safety training. This is in line with research demonstrating that more training will lead to better hazard perception (e.g. Kowalski-Trakofler and Barrett, 2003). The influences of accident probability and outcome severity on their risk evaluations were also of interest, because accepted industry practice in safety risk assessment is to multiply separate evaluations of the probability of occurrence and the expected severity of accident scenarios (Gangolells et al., 2010; Hadikusumo and Rowlinson, 2004; Seo and Choi, 2008). The second hypothesis (H2) is, accordingly, that construction superintendents would assess safety risks by multiplying separate evaluations of the probability of occurrence and the expected severity of accident scenarios. The third hypothesis (H3) is that subjects can identify hazards better in a virtual environment than they can using traditional project documents (drawings and schedules) and photographs.

2. Method

The research method was designed to allow comparison of the hazard identification and risk assessment abilities of construction superintendents with those of civil engineering students (who have had no safety training and have no construction site work experience) and with those of company safety directors, (who have had extensive training and have rich construction experience).

Sixty-one individual subjects belonging to the three different groups were asked to identify the hazards and assess the risk levels in a typical construction project. Some were presented with photographs and traditional construction drawings (the *traditional test*), while others were asked to tour a virtual construction site presented using a 3-sided virtual reality CAVE (the *virtual test*). The same set of 48 safety hazards was represented in both test procedures, in which a variety of hazards were present. We used ANOVA tests to compare performance in different groups and across the two test methods.

The virtual reality (VR) construction site method was chosen because it offers a unique solution to the problem of presenting a subject with hazardous conditions. Concern for the physical safety of experimental subjects precludes the possibility of asking subjects to tour a real construction site and to identify all of the hazards they can. In particular, purposefully creating hazardous conditions – such as missing edge protection – would be immoral and unethical. Simulated environments presented in virtual reality tools are commonly used for research in fields as diverse as cognitive processing of traffic signs (Liu et al., 2010), learning in primary school students (Roussou et al., 2006) and physiological response to stress (Kotlyar et al., 2008).

Lucas et al. (2008) succinctly described the fundamental advantage of the cognitive learning that is achieved through virtual reality (VR) training over learning in a traditional classroom in the specific context of safety training for equipment operators. If learning in general can be achieved through use of VR, it is likely that hazard recognition and risk perception, specifically, can be tested using VR. Thus a secondary aim of the research was to explore whether a virtual environment can be used to test hazard recognition and risk perception. Our hypothesis in this regard was that civil engineering students, construction superintendents and company safety directors can identify hazards better in a virtual environment than they can using traditional project documents (drawings and schedules) and photographs.

2.1. Subject population

Twenty-three civil engineering students, 31 construction superintendents and seven company safety directors) were tested. Of the 61, 28 were tested in the virtual test and 33 in the traditional test (see Table 1 for details). The student volunteers were all final year students of construction management from the Technion – Israel Institute of Technology. Their only prior exposure to hazard identification was the minimal content on safety in an introductory construction management course, possible reading in textbooks, and from a site visit during the course of their studies. The construction superintendents and company safety directors were all recruited from companies that are rated at level 5 (the highest possible grade) by the government registrar of construction contractors.

As can be seen in Table 1, the safety directors' group and the superintendents' group had significantly more years of work experience than the students' groups (with overall population means of 21.8, 17.9 and 0.3 years respectively). Almost all of the safety directors (85.7%) and superintendents (92.8%) had received formal safety instruction while only 34.7% of the students had; and the mean of the instruction hours was highest in the safety directors group and lowest in the students group (101.7, 14.2 and 0.7 h respectively). Six of the seven safety directors (86%) had witnessed at least one work accident, as opposed to 72% of the superintendents and only one of the students (4%).

Table 1
Test subject statistics.

Group	Number of subjects	Mean number of years at work	Number of subjects who had received formal safety instruction	Mean number of prior safety instruction hours	Number of subjects injured at work	Number of subjects who witnessed a work accident
Traditional test						
Students	12	0.5	4 (33%)	0.68	1 (8%)	2 (17%)
Superintendents	19	21	17 (89%)	11.3	7 (37%)	13 (68%)
Safety directors	2	33.5	2 (100%)	37.5	1 (50%)	2 (100%)
Virtual test						
Students	11	0	4 (36%)	0.7	3 (27%)	1 (9%)
Superintendents	13	12.6	12 (92%)	19	8 (61%)	10 (77%)
Safety directors	5	19	4 (100%)	85.7	1 (20%)	4 (80%)

2.2. Safety hazard selection and presentation

The scope of the hazards considered was determined by considering the accident types reported in the construction accident statistics of the US, UK and Israel. The incidence of accidents in each of these regions is summarized in Table 2. Specific hazards that represent a wide range of risk levels were identified by surveying the construction process of a typical building project (detailed below). The expected risk levels were assessed according to the incidence rates in Table 2 and on the basis of earlier work by Sacks et al. (2007) that identified the most common loss of control scenarios for a range of construction activities and provided estimates of the relative probability of their occurrence.

In both the traditional and the virtual test procedures, the hazards were presented to subjects within the context of a construction project. The project used was a 17 story apartment building that was part of a residential development that included four similar towers with a common parking garage and public areas, built in 2009–2011 in Petah Tikva, Israel. The building project was surveyed and photographed to identify hazard scenarios that could represent the accident types selected from the national statistics. The photographs included scenes from ground level (with a variety of stored materials, a tower crane, hoists and other equipment, moving vehicles, scaffolding, etc.), from an internal floor (finishing works such as stucco plastering, electrical and plumbing, flooring, and drywall work) and from the top of the structure where reinforced concrete works were in progress for both vertical and horizontal elements (reinforcing and forming of columns, walls and slabs). The hazards selected for presentation in both the traditional and the virtual tests are listed in Table 3.

The hazards were represented in the virtual construction site by modelling them directly in the building information modelling (BIM) software. They were represented in many of the photographs by editing the images, for example to remove sections of railings and place obstacles.

2.3. Traditional test procedure using photographs

In this test, each subject was asked to examine a set of photographs taken at the construction site and a set of construction documents (drawings and schedule). They were first asked to prepare a list, using a standard form as shown in Fig. 1, of all the hazards they could identify and to detail the possible accident types that could result from those hazards during construction. Once they had completed the first task, they were given a full list of the hazards within the context of related accident scenarios (see Table 4), together with a new set of the same photographs; however in the new set, each hazard was marked in one or more of the photographs with a numbered icon, as shown in Fig. 2. In this, the second task, they were asked to assess the overall risk level of each hazard and accident type using the scale defined in Table 5. Finally, in a third stage, they were asked to once again consider the photographs and drawings and to assess a) the probability that each accident would happen and b) the expected severity of the consequences if the accident occurred. Predefined scales, defined in Table 5, were used for both assessments. These two stages were designed to allow comparison of subjects' evaluations with the common practice in risk assessment of multiplying accident probability by severity as a measure of overall risk level.

2.4. Virtual test procedure

The virtual test was carried out using a simulation model of the same construction site in a virtual reality CAVE. As shown in Fig. 3, a CAVE is a room-size device with computer images projected on its walls to produce a virtual environment. The user (or subject) wears 3D vision goggles and manipulates the environment using a controller. Their location relative to the virtual world is tracked continuously so that the system can to adjust the images and maintain the correct view projection vis-a-vis the user's location and viewing direction. Preparing the virtual construction site required a number of steps: modelling a building structure with structural steel and reinforced concrete components using Building Information Modelling (BIM) software (Eastman et al., 2011); application of 'construction method recipes' to model the intermediate physical states that occur during construction, including modelling of all temporary facilities; export of the model to an appropriate exchange format; importing the model into the CAVE software environment; animation of construction equipment (such as the hoist, tower crane and vehicles) and addition of sound effects.

Table 2
Incidence of construction accidents by type in the US, UK and Israel.

Country and year	UK 2009 (HSE, 2010)			US 2008 (BLS, 2009)		Israel 2007 (Bar, 2011)
Accident severity	Fatal	Non-fatal major[a]	Over-3-day absence[b]	Fatal	Non-fatal major	Non-fatal major
Contact with moving machinery	2	134	270			317
Struck by moving, including flying/falling, object	3	529	1035	115	22,230	471
Struck by moving vehicle	4	68	64	119	3090	740
Strike against something fixed or stationary	2	101	274		8410	681
Injured while handling, lifting or carrying	–	434	2462		11,100	435
Injuries caused by hand tools						719
Slips, trips or falls on same level	1	780	1407		11,520	806
Falls from a height of which	9	989	755	266	13,970	966
– up to and inc. 2 m	–	560	498		–	
– over 2 m	9	266	115		–	
– height not stated	–	163	142		–	
Trapped by something collapsing/overturning	3	27	22			72
Drowning or asphyxiation	2	–	1			
Exposure to, or contact with, a harmful substance	–	43	144	106	4210	82
Exposure to fire	–	13	17	7	400	18
Exposure to an explosion	1	10	4			14
Contact with electricity or electrical discharge	–	34	66			22
Injured by an animal	–	5	18		130	11
Acts of violence	–	11	18	36	90	19
Other kind of accident	–	97	219			451
Injuries not classified by kind	6	11	13			
Totals	33	3286	6789	649	75,150	5824

[a] Non-fatal major – resulting in permanent disability.
[b] Over 3-day absence – resulting in an absence from work of more than 3 days.

Table 3
Accident types and hazard scenarios identified in the typical building project.

Accident type	Selected hazard scenarios
Falls from a height	Unprotected outside edge of a slab or balcony
	Unprotected shaft or hole
	Fixed scaffold without adequate fall protection
	Improvised platform (planks on two ladders)
	Ladder propped against a wall
Slips, trips or falls on same level	Low wall or beam
	Loose plank or block lying where workers pass
	Loose rope or electric cable where workers pass
	Oil spill
Struck by moving, including flying/falling, object	Missing foot boards on a scaffold
	Moving crane with load where workers are present
	Work with loose materials (blocks) at height
	Work with façade elements on a scaffold at height
	Work with unsecured hand tools at height
	Moving construction equipment
Injured while handling, lifting or carrying	Bags of cement/concrete blocks on pallets that require moving by workers
Strike against something fixed or stationary	Formwork or other planks at or lower than head height
	Concrete ledge
	AC ducts hanging low
	Exposed rebars
Exposure to fire	Laying bitumen sheets (gas tank with burner)
Contact with electricity or electrical discharge	Exposed temporary electricity board
	Damaged electrical extension cord
Exposure to, or contact with, a harmful substance	Containers of corrosive materials
Trapped by something collapsing/overturning	Improperly secured slab formwork
	Improperly supported wall formwork

Hazard	**Possible accident type**	**Photograph number**
Unprotected edge of an elevator shaft	*Falling*	*16*
Materials in a tall stack	*Bodily injury while lowering materials by hand*	*15*

Fig. 1. Form used by subjects to identify hazards and possible accident types. The first lines of content provide examples.

After numerous rounds of inspection and iteration for improvement of its representation of the actual construction site, the virtual site was validated in four full-length pilot tests of the experimental procedure with superintendent subjects. One result of their debriefings was the decision to relieve the subject of the onus of navigation in the CAVE, leaving them free to observe their environment.

Each subject was asked to tour the virtual construction site in the CAVE three times. Fig. 3 shows the CAVE setup itself and Fig. 4 illustrates the virtual construction site (Fig. 4 in the online version of this paper includes a short video). The virtual construction site was based on the same building used for the traditional test. The virtual model contains not only the same geometry as the real building, but also has the same temporary features as shown in the photographs. The tour route was pre-set, but the subject could move forward or backward at will and could look in any direction or up or down at any time. They could also bend down if needed to get different perspectives on the scene they were in.

During the first tour, they were asked to prepare a list of all of the hazards they identified. The experimenter recorded their responses using the same form as used in the traditional test. Once

Table 4
List of accident scenarios and hazards presented to subjects in stages 2 and 3 of both traditional and virtual tests.

#	Hazard and accident scenario
1	Falling as a result of slipping on oil spilt on the floor
2	Struck by a falling object as a result of working with loose materials on a scaffold
3	Struck by a falling object as a result of working with loose materials on a scaffold with no foot board
4	Struck by a falling object while not wearing a helmet
5	Struck by a falling object while wearing a helmet
6	Struck by a falling piece of equipment while not wearing a helmet
7	Struck by a falling piece of equipment while wearing a helmet
8	Injured by a sharp tool while working without protective gloves
9	Injured by a sharp tool while working with protective gloves
10	Falling from height over 2 m while working on a scaffold or a balcony with no railing
11	Falling from low height while working near an edge with no railing
12	Falling from height over 2 m while working on a scaffold or a balcony with a flimsy railing
13	Falling from low height while working near an edge with a flimsy railing
14	Falling from height over 2 m while working near an unprotected shaft
15	Falling from height over 2 m while working near a shaft with improvised protection
16	Falling from low height while working near an unprotected shaft
17	Falling from height over 2 m while on an improvised platform (e.g. board between two ladders)
18	Falling from low height while on an improvised platform (e.g. board between two ladders)
19	Tripping and falling over a rope or electric cable on the ground
20	Striking (but without falling) a board or block on the ground
21	Tripping and falling over a board or block on the ground
22	Falling from height over 2 m while working on a scaffold with missing stepping boards
23	Falling from low height while working on a scaffold with missing stepping boards
24	Electrocution from exposed electric wires in an electric distribution board
25	Electrocution from exposed electric wires of a power tool
26	Struck by an object falling from a palette lifted by a tower crane
27	Struck by concrete spilt from a bucket lifted by a tower crane
28	Injured while working with an electric saw
29	Crushed by collapse of slab formwork when concrete is being poured
30	Crushed or injured by falling formwork from supports at ground level
31	Crushed or injured by formwork falling while being lifted by a tower crane
32	Injured by concrete formwork collapse while fixing reinforcing steel or pouring concrete
33	Falling from low height while climbing a ladder propped against a wall
34	Injured by the sharp edge of a reinforcing bar or mesh
35	Falling from low height while walking on a reinforcing mesh in a slab
36	Back injury from carrying a heavy load
37	Run over by heavy machinery in the construction site
38	Run over by a vehicle in the construction site
39	Falling from heights above 2 m as a result of being struck by the boom of a concrete pump
40	Struck by the boom of a concrete pump
41	Stepping on a nail in a board on the floor with no protective shoes
42	Stepping on a nail in a board on the floor with protective shoes
43	Burn or other injury from corrosive chemicals
44	Injured while working with a disc power tool
45	Sickness as a result of breathing dust from sawing stone or concrete
46	Eye injury from cutting reinforcing bars with a disc power tool
47	Crushed or injured from collapse of the tower crane
48	Injured as a result of taking down heavy objects from a tall stack of materials

Fig. 2. Example of a site photograph showing a hazard marked with a number icon.

they had completed this first task, as for the traditional test, they were given the full list of the hazards and potential accidents and were asked to tour the virtual site once again, to assess the risk level of each hazard. In this stage, the hazards were highlighted with numbered 'billboard' icons. Finally, in a third tour of the site, they were asked to assess the probability of an accident for each hazard and the severity of its consequences, again using the same form as used in the traditional test.

3. Results

For each subject we calculated the number of hazards identified and the number of correct hazards identified compared to a predefined list of hazards that could be identified in the environments (traditional test or VR). Additionally we also calculated for each subject the means for assessments of overall risk, probability and severity for all 48 hazards (see Table 6).

We also calculated for each subject the total number of instances of hazard identified for each hazard type, and for each hazard type, the percentage of subjects who identified it (Tables 7 and 8). Additionally, we calculated for each subject the number of times he identified hazards related to Obstacles, Heights, Working on scaffolds or ladders, Dangerous materials, Personal safety and Moving vehicles (Table 9).

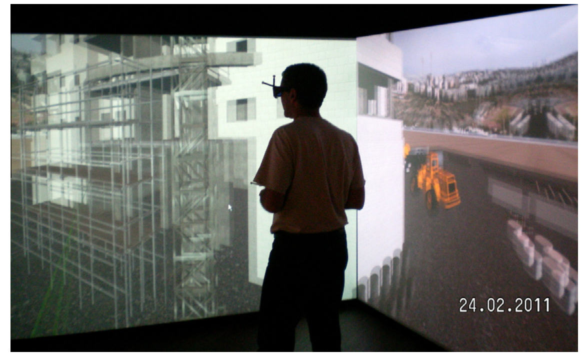

Fig. 3. A subject touring the virtual construction site in the CAVE.

Fig. 4. A view of the top floor of the virtual building with reinforced concrete works were in progress for both vertical and horizontal elements (reinforcing and forming of columns, walls and slabs).

The number of hazards identified was submitted to an ANOVA test with Group (Students and Superintendents) and Condition (traditional test and virtual test) as the manipulated factors. None of the effects was significant ($p > 0.1$). Additionally, the number of correct hazards identified was submitted to a two-way between subject ANOVA test. Again, none of the effects was significant. The mean of assessments of overall Risk was also submitted to an ANOVA. This time, the group effect was significant

Table 5
Scales for assessment of accident severity, probability and overall risk level.

Subject	Numeric value				
	1	2	3	4	5
Accident severity	No injury	Minor injury with no sick leave required	Injury requiring at least 3 days sick leave	Non-fatal major injury	Fatal
Accident probability	Very unlikely/ infrequent	Fairly unlikely/infrequent	Average likelihood	Fairly likely/ frequent	Very likely/ frequent
Risk level	Very low	Low	Medium	High	Very high

Table 6
Assessments of overall risk, probability and severity, mean number of hazards identified, and mean number of correct hazards identified for 48 hazards.

Subjects	Risk level	Probability	Severity	Mean number of hazards identified	Mean number of correct hazards identified
Traditional test					
Students	3.2	2.9	3.3	24	13.5
Superintendents	3.6	3.1	3.4	28.4	12.8
Safety directors	3.2	2.8	3.5	65	21
Virtual test					
Students	3.4	2.9	3.2	26.1	13.2
Superintendents	3.8	3.6	3.5	33	14.6
Safety directors	3.7	3.3	3.7	47.6	16.5

Table 7
The total number of hazard instances identified for each hazard and the percentage of subjects who identified this hazard type, by subject role.

Hazard class	Hazard type	Average number of hazard identifications					
		Students		Superintendents		Safety directors	
		Instances	Type (%)	Instances	Type (%)	Instances	Type (%)
Small obstacle	Board or block on the ground	3.2	87	2.8	87	3.8	86
	Oil spilt on the floor	0.34	35	0.09	9	0.2	29
	A rope or electric cable on the ground	0.69	48	0.48	63	0.71	58
Working on a scaffold or a balcony	No railing	3.2	87	6.1	100	7.2	100
	Flimsy railing	1.4	83	3.5	88	5.5	100
	Improvised railing	0.43	22	0.70	44	0.71	43
	Missing stepping boards	0.21	17	0.77	34	1.57	86
	Object falling	1.21	70	0.51	41	0.57	29
	Improvised scaffold	1.34	70	1.51	78	3.57	100
	Unprotected ladder	1.69	87	2.06	78	3.14	100
	Loose materials	0.39	26	0.32	22	0.14	14
Dangerous materials	Gas tank	0.08	9	0.06	9	0.14	14
	Dangerous materials in tank	0.30	26	0.22	16	0.83	57
Sharp edge of a reinforcing bar	Sharp edge of a reinforcing bar	0.6	35	0.19	22	1.14	71
Electric wires	Electric wires	0.47	39	0.32	31	0.57	29
Large obstacle	Material palette	0.56	48	1.09	50	1	57
	Sand bags	0.13	13	0.06	6	0.14	14
	Garbage skip	0.39	30	0.25	19	0.57	29
Carrying a heavy load	Carrying a heavy load	0.17	17	0.8	52	1	43
	Collapse of shoring under slab formwork	0.34	26	0.67	52	0.85	57
	Faulty closing of wall or column formwork	0.08	9	0.54	35	1	57
Shafts and stairs	No railing	0.82	61	0.64	45	0.42	29
	Improvised railing	0.13	13	0	0	0.14	14
Personal safety	No construction helmet	1.26	70	1.16	68	1.85	86
	No protective gloves	0.30	26	0.48	45	0.14	14
	No protective shoes	0.08	9	0.25	26	0.28	295
	No safety harness	0.56	48	0.51	42	1.14	71
Tower crane	Object falling	0.91	48	1.09	52	1.83	71
Heavy machinery and vehicle	Heavy machinery and vehicle	1.86	52	1.03	55	2.57	71
Earthworks	Piles of soil	0.04	4	0.35	29	0.42	29
Static object or part of a building above eye-level	Collision or knocking into building features	0.52	30	0.25	19	0.42	29
Power tool	Power tool	0.69	40	0.51	36	1.28	86

[$F(1,50) = 12.56$, MSE = 0.1876, $p < 0.01$] indicating that superintendents assessed the level of Risk higher than students (see Table 10). Next, the mean of assessments of Probability was also submitted to an ANOVA. The group effect was significant [$F(1,50) = 4.06$, MSE = 0.3428, $p < 0.01$] indicating that employees assessed Probability higher than students. The mean of assessments of severity was also analyzed with ANOVA. The group effect was significant [$F(1,50) = 4.79$, MSE = 0.0801, $p < 0.05$] as were the interactions [$F(1,50) = 3.93$, MSE = 0.0801, $p < 0.05$]. Table 6 shows a clear difference in mean of assessments of severity between groups such that in the CAVE this difference was larger. In line with this observation, we found that in the CAVE assessments of severity were higher by the superintendents [$F(1,50) = 7.74$, MSE = 0.080076, 0.05]. In the traditional test procedure there was no difference [$F < 1$]. Accordingly there was better performance in the CAVE only in some cases.

Next, the number of hazards identified that were related to 'obstacles' was submitted to an ANOVA. The effects were not significant. The number of hazards related to 'working on scaffolds or stairs' was also submitted to an ANOVA. Only the group effect was significant, [$F(1,50) = 9.70$, MSE = 34.986, $p < 0.01$] indicating that superintendents identified more hazards related to working on scaffolds or stairs than students did. The number of hazards identified that are related to dangerous materials was submitted, next, to an ANOVA and the condition effect was significant [$F(1,50) = 6.07$, MSE = 0.422274, $p < 0.05$] indicating that in the virtual test subjects identified more hazards than in the traditional test. For hazards connected to personal safety equipment, no difference was found. Finally, the number of hazards identified that are connected to moving vehicles was submitted to an ANOVA. Only the condition effect was significant, [$F(1,50) = 40.89$, MSE = 5.3931, 0.05] indicating that in the virtual test subjects could identify more hazards related to moving vehicles than in the traditional test.

For every subject we also calculated the correlations between their evaluations of Risk and Probability and their evaluations of Risk and Severity. We found that the correlations between evaluations of risk and probability were higher than the correlations between risk and severity for only 5 subjects; for 25 it was lower and for 25 it was more or less the same. This indicates that when subjects are asked to identify the overall risk, they tend to place more emphasis on severity than on probability.

In Fig. 5 we present local differences between specific hazards. As can be seen, in many cases subjects identified more hazards in the CAVE. These fell mainly in the classifications of moving vehicles, objects falling from above (specifically from a tower crane), use of power tools, transport of material on palettes, and absence of personal protective equipment (construction helmets). Another interesting difference is that all subjects identified the hazards related to falls from heights where railings were missing, regardless of the presentation method. Superintendents appear to be well aware of this hazard. Some hazards, such as those posed by earthworks, were more easily identified when presented using photographs.

4. Discussion

Summing up the results, superintendents with work experience and more formal safety training assessed the level of risk higher than students with little work experience and little formal safety training. Superintendents also assessed probability higher than

Table 8
The total number of hazard instances identified for each hazard and the percentage of subjects who identified this hazard type, by experiment type.

Hazard class	Hazard type	Average number of hazard identifications			
		Traditional test		Virtual test	
		Instances	Types (%)	Instances	Types (%)
Small obstacle	Board or block on the ground	2.75	85	3.32	82
	Oil spilt on the floor	0.12	12	0.32	32
	A rope or electric cable on the ground	0.60	52	0.57	39
Working on a scaffold or a balcony	No railing	6.39	100	3.78	89
	Flimsy railing	3.42	91	2.5	82
	Improvised railing	0.75	48	0.42	36
	Missing stepping boards	0.75	42	0.53	36
	Object falling	1.15	70	0.35	32
	Improvised scaffold	1.06	67	2.42	89
	Unprotected ladder	1.84	76	2.28	93
	Loose materials	0.51	30	0.1	11
Dangerous materials	Gas tank	0.12	12	0.03	3
	Dangerous materials in tank	0.06	6	0.64	43
Sharp edge of a reinforcing bar	Sharp edge of a reinforcing bar	0.42	30	0.50	32
Electric wires	Electric wires	0.36	30	0.46	39
Large obstacle	Material palette	0.84	52	0.92	46
	Sand bags	0.06	6	0.14	14
	Garbage skip	0.48	33	0.14	12
Carrying a heavy load	Carrying a heavy load	0.9	58	0.21	14
	Collapse of shoring under slab formwork	0.6	52	0.53	33
	Faulty closing of wall or column formwork	0.45	27	0.39	29
Shafts and stairs	No railing	0.75	55	0.6	43
	Improvised railing	0.03	3	0.1	10
Personal safety	No construction helmet	1.39	70	1.14	71
	No protective gloves	0.33	30	0.42	39
	No protective shoes	0.09	9	0.32	32
	No safety harness	0.30	30	0.96	68
Tower crane	Object falling	0.48	30	1.78	79
Heavy machinery and vehicle	Heavy machinery and vehicle	0.45	33	2.78	82
Earthworks	Piles of soil	0.42	33	0.03	3
Static object or part of a building above eye-level	Collision or knocking into building features	0.36	21	0.39	29
Power tool	Power tool	0.30	30	1.10	57

Table 9
Mean number of times participants identified hazards related to obstacles, working on scaffolds or stairs, dangerous materials, personal safety and moving vehicles.

Subjects	Obstacle	Working on scaffolds or stairs	Dangerous materials	Personal safety	Moving vehicles
Traditional test					
Students	7.1	9.0	0.25	1.0	0.4
Superintendents	5.4	14.4	0.11	2.0	0.8
Safety directors	3.0	31.5	0.5	3.0	5.0
Virtual test					
Students	3.7	6.5	0.5	2.2	5.3
Superintendents	4.1	11.4	0.7	3.0	4.1
Safety directors	4.0	14.4	1.2	3.6	3.8

students. Additionally, in the virtual test, superintendents assessed the level of severity higher than students. Superintendents also identified more hazards related to working on scaffolds or stairs. Hypothesis H1 was accordingly confirmed at least in part.

The results in Table 9 show that, in line with hypothesis H3, civil engineering students and superintendents can identify hazards related to moving vehicles better in a virtual environment than they can using traditional project documents and photographs. Although only seven company safety directors participated in the experiment, we could conclude that they identify hazards better than the other subjects, as hypothesis H1 predicted. These results may indicate that ability to identify hazards is positively correlated with work experience and formal safety training. Extensive formal safety training appears to be of great importance in the safety culture studied, since this was the main differentiating factor, although of course the specific job focus of the company safety directors may also influence their ability and performance.

Another implication is that in the safety culture of the subjects the safety directors play an essential role. This result is of concern, since given the strong influence of the superintendent role on workers' behaviour regarding safety (Gillen et al., 2004a,b) and their constant presence on site as opposed to infrequent visits of safety directors, site safety would be better served by superintendents with better hazard identification and assessment skills.

The influences of accident probability and outcome severity on risk evaluations were also of interest, because accepted industry practice in safety risk assessment is to multiply separate evaluations of the probability of occurrence and the expected severity of accident scenarios. We found that, in contrast with the assumption of hypothesis H2, when subjects were asked to identify the overall risk a majority (46% of subjects) consider mostly severity, while only 9% consider mostly probability. The remainder appears to consider both severity and probability. This behaviour is common for lay people (Beck, 1984; Prohaska et al., 1990; Weinstein, 2000) and is to be expected from students, but not from construction professionals. The result therefore raises questions concerning the safety culture of the superintendents' group. The same result was not found for the safety directors' group.

Table 10
Results of detailed hypotheses testing.

Effect	Hypothesis group	Accept (p value) or reject
Superintendents identified more hazards than students	H1	Reject
In the virtual test subjects identified more hazards than in the traditional test	H3	Reject
Superintendents identified more correct hazards than students	H1	Reject
In the virtual test subjects identified more correct hazards than in the traditional test	H3	Reject
Superintendents assessed the level of risk higher than students	H1	Accept ($p < 0.01$)
In the virtual test subjects assessed the level of risk higher than in the traditional test	H3	Reject
Superintendents assessed probability higher than students	H1	Accept ($p < 0.01$)
In the virtual test subjects assessed probability higher than in the traditional test	H3	Reject
In the virtual test assessments of severity were higher by the superintendents	H1	Accept ($p < 0.05$)
In the traditional test assessments of severity were higher by the superintendents	H1	Reject
Superintendents identified more hazards related to 'obstacles'	H1	Reject
In the virtual test subjects identified more hazards related to 'obstacles' than in the traditional test	H3	Reject
Superintendents identified more hazards related to working on scaffolds or stairs	H1	Accept ($p < 0.01$)
In the virtual test subjects identified more hazards related to working on scaffolds or stairs than in the traditional test	H3	Reject
In the virtual test subjects identified more hazards related to dangerous materials than in the traditional test	H3	Accept ($p < 0.05$)
Superintendents identified more hazards related to dangerous materials	H1	Reject
In the virtual test subjects identified more hazards related to hazards connected to personal safety equipment than in the traditional test	H3	Reject
Superintendents identified more hazards connected to personal safety equipment	H1	Reject
In the virtual test subjects identified more hazards related to moving vehicles than in the traditional test	H3	Accept ($p < 0.05$)
Superintendents identified more hazards related to moving vehicles	H1	Reject

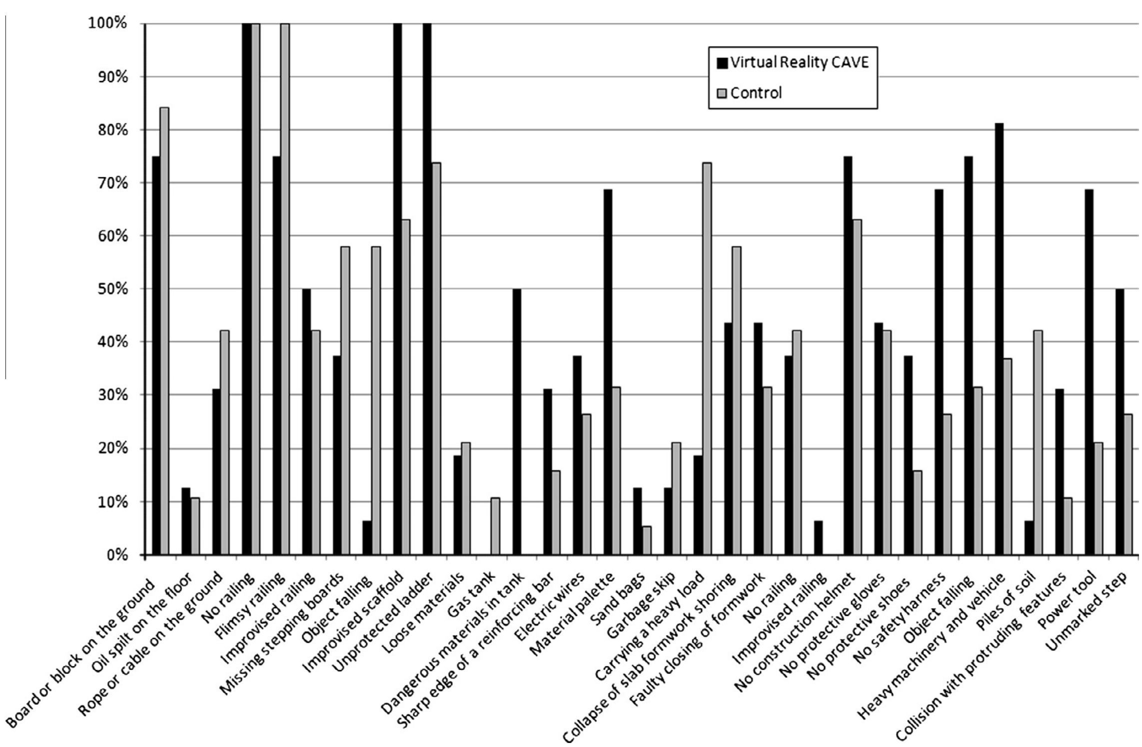

Fig. 5. Rates of success in hazard identification using VR and using photos for a range of hazard types.

The results in Table 6 may confirm that superintendents' ability to identify hazards is a result of work experience and formal safety training, which the students lack. If that was true, however, we would expect for example that the ability of superintendents (as a distinct group) to identify hazards would be positively correlated with their work experience in years, or that superintendents with more formal safety training would have better ability to identify hazards. We did not find such results, as is clearly apparent from Figs. 6 and 7, and hypothesis H1 is therefore rejected. On the one hand, this may indicate that very little experience and very little formal safety training is sufficient to achieve some minimal ability for hazard identification and perception. On the other hand, safety managers, who had significantly more training than either of the superintendent or student groups (71.9 h average), identified far more hazards. Although this result appears to indicate that thorough training is needed to achieve effective levels of hazard perception, it could also be the result of a different mindset regarding safety on the part of safety managers for whom construction safety is the main focus of their job. One should also keep in mind that the sample size was too small to reach firm conclusions. For these reasons, further research is needed to investigate this question. The primary concern, however, is that the current

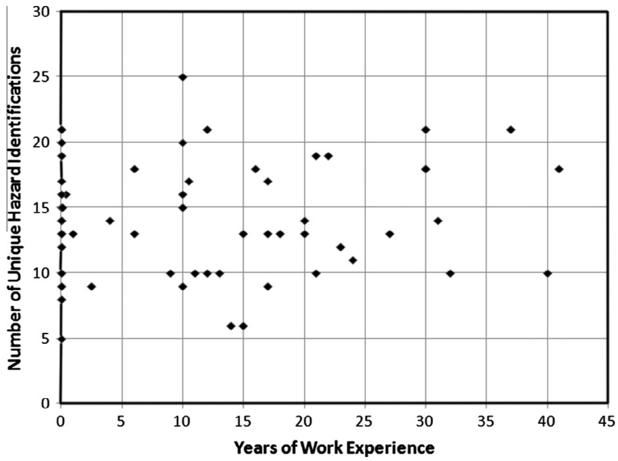

Fig. 6. Influence of work experience on hazard identification skills.

Fig. 7. Influence of safety training (logarithmic scale) on hazard identification skills.

methods and/or extent of safety training of construction superintendents appear to be ineffective. This should be the subject of further research.

The study focused on safety managers and construction superintendents, who are responsible for the safety of the laborers under their supervision, but did not test construction laborers. Evaluating laborers' perceptions of hazards would shed additional light on their needs for training, and is an important goal for future research.

An additional limitation is that the virtual work environment lacks the human interactions through which hazards can be identified in real situations. Thus actual performance in identifying hazards may be better in the real world than in either the virtual or traditional tests. Yet, given the moral and ethical constraints on exploring hazard identification on site, future researchers might consider experimental setups using VR in which subjects virtually perform work, or testing pairs of subjects in the CAVE to enable discussion among them.

5. Conclusions

As expected, most subjects identified more hazards correctly in the virtual environment than did subjects who studied photographs and documents. However, the control group of civil engineering students, who had little or no experience on site or safety training, did not identify significantly fewer hazards than superintendents. Even with many years of experience, the construction work superintendents were unable to identify all of the hazards that safety managers were able to identify in either the traditional procedure or in the virtual environment. In addition, the apparent lack of correlation between hours of safety training and work experience on the one hand, and hazard identification and perception skills on the other hand, is of primary concern.

Finally, the construction superintendents assessed risk levels with greater weight given to the component of accident severity than to the component of probability, raising a question concerning their safety culture. This may be a localized result, dependent on the broader industrial culture of the country or on attitudes specific to the construction industry; it is worthy of further study across different contexts.

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