

Framework for Integrating Safety into Construction Methods Education through Interactive Virtual Reality

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Abstract: Construction accidents, injuries, and fatalities have not declined significantly, despite arduous efforts of researchers, safety professionals, and strongly-enforced safety laws. Safety education is crucial in promoting safe and healthy construction work environments; however, current pedagogical methods and tools at the tertiary level do not sufficiently engage students or provide practical experience to support the acquisition of safety knowledge. This paper aims to address the problem by proposing a novel approach that integrates safety with construction materials and methods education. A system is proposed comprising of three sequential modules: (1) safety and hazard lecture (SHL) module; (2) hazard identification game (HIG) module; and (3) student evaluation and assessment (SEA) module. The pedagogical suitability of the system is evaluated by a series of trials where students interacted with instructors. Interim results indicate that the system offers an innovative medium for experientially improving hazard identification ability, transferring safety knowledge, and engaging students. Insights of matching safety with construction methods are also discussed in the paper. DOI: [10.1061/\(ASCE\)EI.1943-5541.0000261](https://doi.org/10.1061/(ASCE)EI.1943-5541.0000261). © 2015 American Society of Civil Engineers.

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Introduction

Construction jobsites are among the most dangerous workplaces, with fatalities and recurring accidents still plaguing the industry (Le et al. 2014a). These occur for various reasons; however, one underlying cause relates to deficiencies in the education and training of construction project personnel (Guo et al. 2012). Efficient and effective safety training programs have the potential to improve safety performance by preventing accident occurrence. Safety training also improves behavioral attitudes and makes accidents more predictable. Currently, at the industry level, typical safety training programs are delivered through on-site workshops. Some of these include mentoring programs and use buddy systems to help orient new employees (Vinodkumar and Bhasi 2009). However, a large proportion of these have proven ineffective in sufficiently preparing workers and graduates for the work site. On the other hand, at the tertiary institution level, construction curricula vary in their approaches to safety education; with some programs including safety topics in their curricula while others do not. Furthermore, the majority of the programs that do consider site safety matters utilize teaching strategies that have been criticized for being passive, boring, and not sufficiently motivating (Gambatese 2003). As stated by Perdomo et al. (2005), the teaching tools in construction education are unable to sufficiently include complex details, realistic scenarios, and construction problems that can enhance learning. This is further emphasized by Forsythe (2009), who stated that a

conundrum exists between construction principles taught in the classroom and an applied understanding of what actually happens on construction jobsites. As a result, many graduates enter the construction industry with inadequate construction safety experience and knowledge.

In attempts to improve tertiary education, virtual reality (VR) technologies have been applied and proved beneficial in various disciplines (Sampaio et al. 2010a). VR applies to computer-generated environments which are experienced through sensory stimuli. The medical, engineering, and manufacturing disciplines have successfully used VR to create innovative learning environments that simulate realistic physical spaces (Aurich et al. 2009). Similarly, the construction industry has had its share of VR systems and advanced visualization technologies, with recent research efforts in construction-worker training (Li et al. 2012); construction work inspection (Gimeno et al. 2011; Kwon et al. 2014); site safety management (Park and Kim 2013), and construction plant operations (Guo et al. 2012). Despite these studies, accident rates in construction still remain high. Very few studies have focused on the application of these technologies to safety education at the tertiary institution level. Hence, this research aims to enhance traditional construction education by comprehensively incorporating safety content to current construction engineering and management (CEM) curricula.

Currently, CEM programs include criteria requiring graduates to demonstrate a variety of proficiencies and an understanding of construction processes, communication, methods, materials, equipment, and safety etc. Even though construction safety is occasionally included, it is usually a low priority among other learning outcomes. It is imperative that construction curricula reorient their educational processes to meet the needs of the industry and address its persistent safety problems. Construction methods courses give students an opportunity to learn about various building systems, relevant construction terminology, and the critical roles of building methods and materials. Typical course objectives require students to: understand basic construction terminologies; understand properties of common building materials, and understand the assembly processes for building systems in detail. However, the safety

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aspects associated with these building processes are not considered. Incorporating safety into construction methods courses presents an opportunity for students to acquire safety knowledge and develop their safety awareness in relation to specific building works and processes. Utilizing interactive VR to deliver safety information would enable learners to clearly visualize site scenarios and hazards in conjunction with related construction processes.

Through the use of VR, QR codes, and mobile devices, the proposed system creates immersive, accessible, and captivating learning environments that afford learners an experiential opportunity to acquire safety knowledge and improve their hazard-identification abilities. VR is adopted as a cognitive learning platform allowing learners to examine virtual site environments, identify hazards, and perceive the direct consequences of their actions, without detrimental real-life consequences. This paper reviews the current state of construction safety training and education, and then discusses the application of prominent visualization technologies in construction education. An overview of the research methodology for the study is provided, and a virtual construction safety education system (VSES) is proposed based on the limitations of the existing pedagogic approaches. The systems' structure is introduced and a framework for applying VR in construction education is provided. Next, the system functions and constituent modules are detailed. Hands-on system trials are conducted with two prototype scenarios in order to assess the pedagogical suitability of the VSES. Finally, the results of this study are discussed and future research directions are suggested.

Methodology

A methodology involving several key processes was adopted in the study. Initially, a literature review was carried out, students and educators were interviewed, and construction course curricula were analyzed to assess the state of construction safety education. The literature review showed that safety education is not considered as a high priority at tertiary level and there is no stand-alone construction safety course in the current curriculum in Korea. Accident cases were also collected and analyzed, confirming the need for improved hazard identification capabilities among construction personnel. Based on these analyses, the required educational contents including safety rules and safe work procedures were identified for the VSES system. Specific contents pertinent to the Korean construction industry were acquired through the Korean Occupational Safety and Health Agency (KOSHA) rules and regulations and Standard Risk Evaluation Model. A prototype system was then developed to integrate VR safety scenarios into construction curricula with the hypothesis that this approach would improve learners' safety knowledge and hazard recognition ability. The system was then implemented through a series of lectures with 25 students, and evaluated through hands-on trials with questionnaires and interviews in a building construction class.

Literature Review

Issues in Construction Safety Training and Education

Safety training and education have been proven to affect safety performance on construction jobsites. Through safety education and training, project personnel can become more aware and knowledgeable of potential construction site hazards and appropriate mitigation measures. Effective safety education and training provide knowledge, which helps reduce injuries and fatal accidents on construction jobsites. This knowledge is usually gained through safety

toolbox meetings, specialized training programs, safety courses in universities, and on-the-job experience (Gambatese 2003). Nowadays majority of safety training programs take place on construction jobsites, making use of educational presentations and videos that usually span many hours. These training programs provide workers with detailed information about site risks and hazards, as well as safe behavior and practices. However, workers play a passive role in these programs, hence often finding them boring and insufficiently engaging (Xie et al. 2006). In many cases, these programs are ineffective because they do not adequately motivate trade workers and project personnel to learn about safety and health matters.

It is also essential that future construction managers, project managers, and other project personnel acquire an understanding of construction site safety. Even though they may not perform actual fieldwork, their safety knowledge and interactions with site personnel have a significant influence on jobsite safety (Gambatese 2003). Tertiary safety education creates an opportunity to prepare future project personnel for the construction jobsite and can be used to supplement on-site training. Some construction management programs already include safety education in their curricula; however, it is generally not considered a high priority (Jaeger and Adair 2012). As stated by Gross and Jovanis (2008), the use of existing safety research material to provide construction students with a more-fundamental educational experience in safety is limited. Most construction programs that include safety education have it as an individual course. However, in reality, safety matters are not considered in isolation. In real-life situations, safety matters are often interwoven into other activities. Site safety is related to the construction methods, materials, equipment, and machinery being utilized on the project. Hence, safety matters should ideally be integrated with their corresponding subject areas.

A further limitation of construction education is limited student engagement and motivation. Moreover, due to the nature of construction work, safety education has to take place in hands-off, off-site environments where learners can only listen and watch without actively participating. Construction courses use two-dimensional images and videos to assist students in visualizing complicated construction tasks and environments. However, students cannot interact with images and videos; hence, they play a passive role in their learning and cannot fully perceive jobsite hazards and risks. To date, very few studies have taken advantage visualization technologies in order to improve construction safety education (Jaeger and Adair 2012). There is currently a need to improve construction safety education by incorporating recent technological advances in simulation and modeling (Goedert et al. 2011).

Visualization Technology and Mobile Devices in Construction Education

Computer technologies have significant impacts on student achievement, with benefits such as increased instructor–student interaction, collaboration, problem-solving, and student inquiry skills (Behzadan and Kamat 2011). Visualization technologies have recently been advocated to provide support for construction safety education (Guo et al. 2012).

Studies have considered the use of building information modeling (BIM) and game simulation techniques for the development of educational and training tools (Park and Kim 2013). Clevenger et al. (2012) leveraged BIM to enhance construction management and civil engineering education. Games have been proven to be effective in supplementing traditional teaching methods (Shiratu and Fletcher 2007). Le et al. (2014b) points out that educational games reinforce cognitive skills and emphasize learning by doing,

collaboration, reflection, and frequent feedback among students and teachers. Furthermore, students have been observed to show higher levels of concentration and grasp new concepts faster when exposed to 3D materials (Bamford 2010). Nowadays countless games make use of immersive virtual environments, based on VR, allowing users to explore 3D interactive environments in real time (Sampaio et al. 2010a).

Several studies have considered VR as a tool to complement traditional construction education (Perdomo et al. 2005). Sampaio et al. (2010b) explored the applicability of VR, computer aided design (CAD), and 3D modeling in architectural, engineering, and construction education. Lin et al. (2011) conducted a pilot study of a 3D game that enabled university students to assume the roles of safety inspectors and identify potential jobsite hazards. In addition, Li et al. (2012) developed a new safety-assessment method, named 4D Interactive Safety Assessment, which utilized virtual scenarios in assessing construction workers. The system presented workers with virtual risk scenarios relating to their project and a range of possible actions for selection. Dickinson et al. (2011) developed a serious game allowing students to explore 3D environments and learn about trench health and safety. As defined by Michael (2006), serious games are games in which education is the primary goal, rather than entertainment.

Studies have confirmed that VR and serious games can be used to create authentic, meaningful tasks and activities for construction education. Furthermore, by supporting engaging simulated environments, VR and gaming can stimulate deeper learning, promote student interaction, and allow better situational awareness. However, studies have not delved deeply into how VR gaming can be incorporated into existing construction safety course contents at higher education institutions. To date, most research focus on game development and applying VR in isolation, without considering their actual practical applicability alongside classroom activities.

Over the past few years, the advent of multimedia-capable mobile technologies has also stimulated substantial interest in various industries. Application developers now have options to exploit various technologies such as *Java*, *Open C*, *Python*, etc. to create compelling mobile content. As stated by Fierres et al. (2008), mobile learning enables the application of theoretical knowledge learned in a practical scenario and reflection on the applied knowledge. Educators and developers have begun considering the implications of mobile devices on learning environments; however, limited studies have done so for construction education. Mobile devices can serve as powerful tools in higher education, making information more accessible and delivery more efficient, personal, and culturally acceptable (El-Hussein and Cronje 2010). Mobile devices have immense potential to enhance game-based learning experiences through location-based functions such as augmented reality, geotagging, and QR codes (Epper et al. 2012). QR codes are two-dimensional bar codes that can be read on mobile devices (camera phones), enabling a user to complete an action. Core actions with QR codes include linking to web-based resources and providing additional information (Ramsden 2008).

Need for Integrating Safety into Construction Engineering and Management Curricula

Effective tertiary safety education has the potential to equip construction students with safety knowledge to proactively reduce accidents in construction sites. Safety education plays a crucial role in promoting healthy and safe work in construction sites. However, there is no stand-alone safety course in the Korean construction curriculum. Building Construction is a compulsory 1-year course

that provides construction students with fundamental knowledge about construction processes, methods, materials, equipment, cost analysis, etc. Even though construction safety matters are occasionally included and discussed, they take a low priority since demonstrating safety knowledge is not considered a main learning outcome in construction classes. In addition, interviewing construction students ascertained that safety is not considered alongside construction processes and methods; educational contents lack interaction and provide limited motivation. These curricula barely afford learners an opportunity to develop a comprehensive understanding of safety matters prior to exposure to real jobsite hazards. As a result, graduates with inadequate construction safety experience and knowledge perform unsafe actions that could cause accidents and fatalities on site. Integrating safety into lessons in Building Construction classes would present a great opportunity for students to acquire necessary safety knowledge and develop their safety competency. Furthermore, utilizing interactive VR to incorporate safety education with construction methods would enable (1) visualizing construction sequences with safety contents to improve site environment perception and safety cognition; (2) motivate construction students to learn about safety matters; and (3) provide an active learning experience to support the acquisition of safety knowledge. In doing so, the VSES, which takes advantage of the aforementioned benefits of VR, Game Based Learning, and mobile devices, is proposed. The following section provides an overview of the methodology for the study.

Virtual Construction Safety Education

Virtual Construction Safety Education Framework

As illustrated in Fig. 1, the VSES framework shows the educational features of the proposed system and how these would enable the achievement of safety competency in construction management students. Accordingly, the system was designed with three modules:

1. The safety and hazard lecture module (SHL) was developed to captivate and motivate students and enable situational awareness to support safety knowledge acquisition;
2. The hazard inspection game (HIG) module was developed to engage learners, allow practice and virtual experience, and support communication in order to enable the application of safety knowledge; and
3. The student evaluation and assessment module (SEA) focuses on assessing learners safety knowledge and behavior in virtual environments that are designed to resemble a real jobsite.

Through this process, this research aims to provide safety information and experience, develop safety knowledge, and influence safe behavior in construction management students.

In order to develop virtual scenarios for the full VSES, several steps are required. As shown in Fig. 2, the matching of various contents is necessary. Initially, accident cases, construction-methods textbooks, and Korea Occupational Safety and Health Agency (KOSHA) training documents are analyzed. Based on the analysis, a suitable hazards classification is determined for the VSES. A trade-oriented work breakdown is utilized, based on the KOSHA safety evaluation standard and the fundamentals of building construction textbook (Allen and Iano 2013). Subsequently, safety rules, regulations, hazards, and accident cases are matched with analogous textbook sections. Afterwards, the VSES virtual scenarios are developed. The scenarios are stored in three databases, namely: (1) lecture scenario (LS) database; (2) game scenario (GS) database; and (3) test/exam scenario (TS) database. A multilayered MySQL database incorporating a data manipulation subsystem is

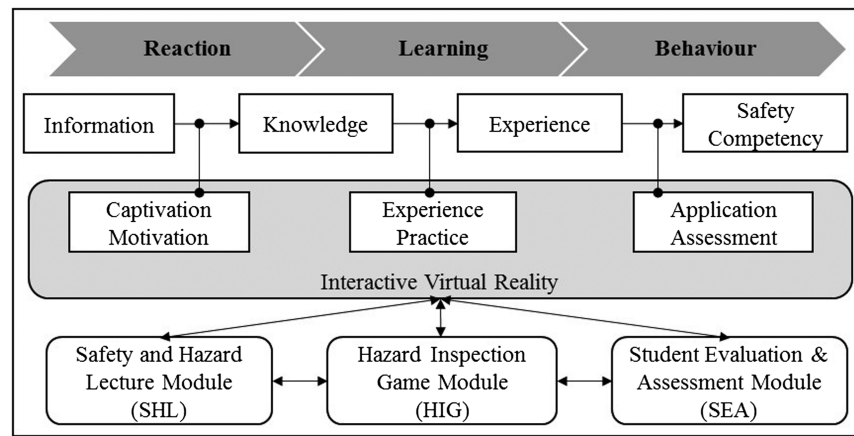


Fig. 1. VSES framework

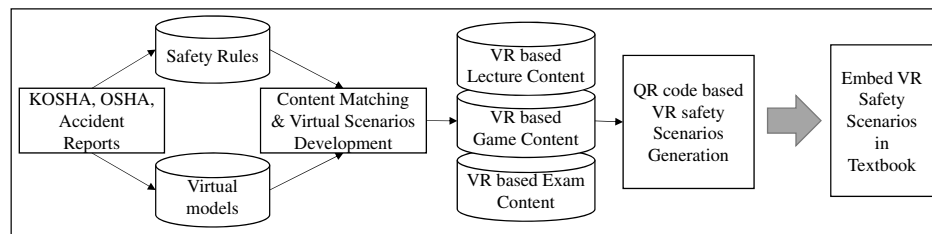


Fig. 2. VSES content development process

proposed in order to allow curriculum developers and educators to access, add, modify, and delete virtual scenarios as required. QR codes are generated and embedded in their respective locations for each virtual scenario.

Virtual Construction Safety Education System (VSES) Modules

A system comprising of three modules is proposed, namely: (1) the safety and hazard lecture (SHL) module; (2) hazard identification game (HIG) module; and (3) student evaluation and assessment (SEA) module. These modules are designed according to the VSES learning model to enhance conventional construction safety education by using interactive VR technology to create stimulating scenarios, examples, and engaging games as well as captivating and motivating environments, all of which facilitate experiential learning. The functions and processes in each module are as follows.

Safety and Hazard Lecture (SHL) Module

The SHL module is initiated with an introduction to the safety topic for the class. Students use their smart devices and textbook QR codes to access virtual scenarios from the LS database, which establish the context for the lesson. Through this, learners can clearly visualize jobsite environments while acquiring safety knowledge. The lecturer's role involves eliciting brainstorming, discussion, and deep thinking through open-ended questions concerning the displayed scenario. The SHL takes up an inductive approach, supporting critical thinking and constructivist learning. Its central purpose is captivating and engaging students from the start.

Principles and approaches to safety and hazard mitigation are taught, relevant safety rules and regulations are discussed, and

conventional text, pictures and diagrams are supplemented with VR-based 3D scenarios. Situational awareness, simulations, and scenarios enhance students' perception of site environments and existing hazards and risks. These visualizations show ideal work methods together with safe and unsafe work environments and worker actions based on KOSHA regulations and accident cases in order to improve learners' hazard cognition. With an educator's guidance, learners identify conditions that are precursors to accidents and loss of controlled conditions in example cases. To conclude the module, students participate in group discussions to reflect on the safety and hazard topics covered. After the lecture, students should be aware and knowledgeable of the material and worker-based and environmental hazards associated with the types of construction work under consideration.

Hazard Identification Game (HIG) Module

The hazard identification game module emphasizes practice and applying the knowledge acquired through the SHL module. The HIG is designed to give students an experiential opportunity to practice predicting, identifying, and responding to hazards on construction sites. The development of these skills is crucial because site safety performance is dependent on construction personnel and their ability to identify and respond to hazards.

Through smart devices, learners connect to a virtual construction site scenario via QR codes in their handouts/textbooks and receive instructions in the mobile graphic user interface (GUI). The game comprises of two core activities: (1) hazard identification activity, and (2) hazard response activity. For the first activity, students are instructed to work in teams and explore the virtual site and recognize all the hazards before any accidents occur. This activity allows peer interaction among students. Moreover, learners

can combine their knowledge with their situational observations in the virtual environment. If students do not identify the hazards on time, accidents occur in the virtual scenario. With the touch-screen functions and navigational keypads of mobile devices, students virtually explore site environments from a first-person perspective and click on various virtual elements such as workers, materials, machinery, and work areas. After a scenario component is clicked, a drop down list is displayed and students have to click the option that best describes the hazard in the scenario being viewed. The game is successfully completed when all the hazards are identified on time and no accidents occur. For the second activity, learners are required to describe how they would respond to the observed hazards. The game allows students to reflect on the effects of their actions virtually, without any consequences in real life. Students are encouraged to communicate and describe what actions are necessary to prevent accidents and injuries. Lastly, the lecturer checks and confirms the students' answers and responses for both activities. Students also have an opportunity to clarify any uncertainties and issues encountered and get feedback regarding their in-game performance.

Student Evaluation and Assessment (SEA) Module

The student evaluation and assessment module is designed to assess the safety knowledge and hazard recognition capabilities of students after the SHL and HIG modules. Its purpose is to ensure that construction students have the ability to apply their safety knowledge to realistic site scenarios. Learners are evaluated with a novel approach using VR-based tests, exams, and assignments, whereby students can view 3D simulations of construction site processes. Three types of questions are proposed for this module: First, multiple-choice questions (MCQs), which include written questions just like traditional tests and exams, are used; however, potential answers are provided using virtual contents through QR codes rather than written text. This approach allows students to clearly visualize the context for questions being considered, whereas such scenarios are typically described using text and depicted with pictures traditionally. Visual learners are disadvantaged with such approaches. Second, Site Management Scenario Questions, which are more detailed than the aforementioned MCQs, are posed. Students are required to inspect a complex building site with numerous activities taking place simultaneously. A picture of the entire building site is provided but all the construction activities taking place cannot be viewed simultaneously. Hence, the picture is enhanced with QR codes, which link to detailed virtual scenarios of specific areas on the site. Students are required to identify hazards, describe their nature, and explain suitable mitigation strategies. Finally, Job Safety Analysis (JSA) Review Questions are given. JSA is a formal method where planned activities are identified, split into subactivities, and their corresponding risks are identified. Students are required to view a virtual site environment and compare it to its corresponding JSA document and assess whether all the hazards and risk have been correctly defined and appropriately considered.

VSES Prototype Development

This section describes the VSES prototype features and its implementation. The development process involved creating a virtual site, virtual scenarios, and game scenarios to test the VSES's educational applicability and the pedagogical validity of its constituent modules. The prototype implementation process is explained as follows.

Virtual Content Development

The prototype VSES involved the deployment of a virtual environment and animation for the SHL module; and a virtual game scenario for the HIG module. The majority of the virtual contents were developed using *Blender*, a free and open-source computer graphics software product with features including 3D modeling, UV unwrapping (3D modeling process of making a 2D image representation of a 3D model), texturing, rigging, animation, and a built-in game engine. The *Blender* game engine is written in C++, and includes support for python scripting language. The study implemented this software primarily because it is free, fast, relatively easy to use, and has a diverse range of features comparable to mid-high range commercial and proprietary software. The prototype development process began with modeling a building under construction and its surrounding site and background (Fig. 3). Colors were assigned and realistic textures were added to building components. Next, ambient occlusion shadows were calculated and added to material textures. Subsequently, lighting was set up for the site scene. Construction worker models were also developed for the virtual animation and game scenarios. Armature was created for worker characters, and through rigging, realistic and natural character movement was enabled. The characters were animated and the view of the virtual environment was changed by animating the camera based on a key frame method.

Virtual Scenario Development

In order to evaluate the VSES and its constituent modules, two virtual scenarios and a game were developed. A sample worksheet was developed with QR codes that would directly connect to the web-based virtual content. The following section discusses each of the virtual scenarios and their utilization.

Concrete Works Scenario

In evaluating the SHL module, two virtual scenarios focusing on concrete work were developed. Concrete work was chosen since it is one of the most commonly-used building materials, playing an indispensable role in modern building, design, and construction. Through smart devices, learners accessed virtual animations from the LS database, portraying laborers pouring concrete for columns. As illustrated in Fig. 4(a), one animation illustrates the ideal situation with appropriate personal protective equipment (PPE); while the second one depicts work without the required PPE. Even though PPE do not guarantee permanent protection of the wearer, they serve as a last line of protection against hazards. The core purpose of these visualizations was to enhance learners' site perception and situational awareness while teaching common hazards and the importance of protective wear (such as glasses, long sleeve shirts and gloves) in conjunction with pertinent concrete construction methods.

Temporary Works Scenario

The HIG is designed to comprise of several virtual scenarios, with each one focusing on a specific area of a virtual site. The scenarios depict various construction activities giving students an opportunity to apply their safety knowledge and improve their risk cognition. High-fidelity simulations are paired with gameplay dynamics in order to increase student engagement and enhance learning. In order to evaluate the HIG module, a virtual scenario involving temporary works was developed, since accident case analyses revealed that many jobsite injuries and fatalities involve work on temporary structures such as formwork, false-work, temporary bridges, etc. Temporary works are defined as engineered solutions used to



Fig. 3. Model of construction site and background



(a)



(b)

Fig. 4. (a) Animations illustrating workers with and without PPE; (b) visualizing consequences of actions in HIG

support or protect existing structures or permanent works during construction.

Students accessed the HIG through their personal smart devices and QR codes embedded in lesson notes. The graphic user interface (GUI) linked to the GS database and displayed the hazard identification task instructions, followed by a site scenario showing two workers carrying a formwork panel away from a cured concrete column. Along the laborers walk path, there is a partially protected opening, an electric cable, and bricks lying around. Students were required navigate through the virtual environment, identify all the hazards, click on the relevant elements, and select the right hazard description before an accident occurs. If hazards are correctly identified no accidents occur, whereas if hazards are incorrectly or incompletely identified, an accident occurs on the virtual site [Fig. 4(b)].

Through this, learners can perceive the outcomes of their actions. Subsequently learners explain the hazards and appropriate elimination and mitigation strategies. Fig. 5 depicts the step-by-step process of participating in the HIG. Fig. 5(a) portrays the QR scanning applications mobile interface, which enables learners to scan QR codes through their smart-device cameras. Additionally, students may scan QR codes, which have been saved in their mobile devices through the photo scan option. A history of recently-scanned QR codes and recently-accessed web pages is also available. Fig. 5(b) illustrates the virtual game scenario that the QR codes connect to. As seen on the top right side of the image, a timer is included, showing the amount of time students have remaining to finish the hazard identification task. A back button is also available, to allow students to return to previous scenarios and the instructions page. A mobile directional pad is available on the bottom right of the HIG interface, allowing navigation through the virtual site. Fig. 5(c) illustrates the options that pop up after students click on a virtual site component with the touch-screen function of their

smart devices. A red tick mark appears next to options that have been selected on the game interface. In this scenario, the correct options that should be selected, are (1) the opening has an unprotected side; and (2) the site is untidy; blocks and wires should be moved aside. Fig. 5(d) illustrates a pop-up that appears if students do not correctly identify the hazard. Students may then retry the hazard identification, and if the educator deems it necessary, an explanation of the hazards in the scenario may also be provided. Lastly, students are required to state what type of guardrails, barriers, and fall protection will be required to make the work area safe as part of the hazard-response activity.

Evaluation and Results

Following the prototype system development, a series of studies and trials were conducted to confirm the VSES would fit the needs of tertiary construction safety education. The VSES was implemented in a third year Building Construction Class, in conjunction with the concrete works chapter being taught at the time. The system was applied to integrate safety knowledge with construction methods and materials knowledge pertaining to concrete works. This section discusses the evaluation scheme deployed in validating the VSES framework and prototype. An evaluation scheme comprising of three phases was deployed: (1) concept and interface evaluation; (2) effectiveness evaluation; and (3) a performance based comparison, which would be carried out in a future study, as illustrated in Fig. 6.

Phase 1: Concept and Interface Evaluation

Phase 1 was divided into two subphases, a preliminary concept evaluation and an interface evaluation. Phase 1.1 was conducted during the development of the prototype VSES to review and



Fig. 5. Hazard inspection game process: (a) QR scanning application mobile interface; (b) virtual game scenario; (c) selecting options in hazard inspection game; (d) pop-up after accident occurs

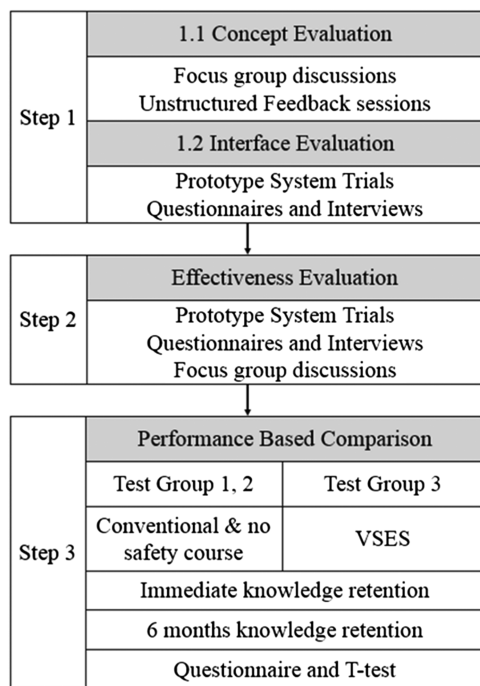


Fig. 6. VSES evaluation scheme

ascertain the potential of the VSES for construction education. Participants included construction class lecturers, construction managers, and undergraduate construction management students from Chung-Ang University, Seoul, South Korea. The preliminary concept evaluation was a subjective study conducted through unstructured feedback sessions. Participants were presented with a conceptual overview of the VSES and its envisaged usage. Subsequently, session attendees engaged in discussions and provided feedback on the system. Educator participants agreed that the VSES would improve student's safety knowledge since current construction curricula barely include any safety content. Furthermore, they expected the VSES to sufficiently engage students and virtually provide practical experience to enhance safety learning. Learner participants emphasized the VSES to be fun, engaging, and capable of effectively transferring safety information.

Phase 1.2, the interface evaluation, was conducted after Phase 1.1, when the prototype VSES development was completed. Students participated in system trials with the SHL and HIG modules of the VSES. After trials, 25 students filled out a 5-point Likert scale questionnaire ranging from (1) strongly disagree to (5) strongly agree in order to compare the VSES system with traditional paper-based lectures. Five categories relating to the VSES interface were evaluated: (1) clarity of instructions; (2) ease of use; (3) interactivity with virtual environment; (4) comfort using a smart device, and (5) engagement (Le et al. 2014b; Park and Kim 2013).

As illustrated in Fig. 7(a), participants agreed that instructions were provided clearly in VSES trial system. They described the system as "straightforward," and barely encountered any difficulties in the SHL and HIG modules. The HIG GUI was considered simple, intuitive, easy to follow, and more engaging and interactive than traditional paper-based lectures. Learners were very comfortable and felt more actively involved with using their smart devices in the classroom. Furthermore, students considered the virtual content graphics apt for mobile device screen sizes. Even though students typically use their smart devices for self-directed informal

learning, they commented that the VSES would fit well into formal academic construction methods learning.

Phase 2: Effectiveness Evaluation

Prior to full scale system implementation, a team from the Construction Technology Innovation Laboratory implemented the VSES through a series of lectures and trials in a 3rd year building construction class with 25 learners from the Department of Architectural Engineering, Chung-Ang University, Seoul, South Korea. The evaluation participants were given an introduction and background information on the study. Volunteering students used an iPhone to connect to the SHL animations and participate in the HIG and then provided feedback on their learning experiences. Discussions were also held with professors, and feedback and recommendations were received. The evaluation process ranged from 10 to 15 min per learner, and through a 5-point Likert scale satisfaction survey, the systems effectiveness was assessed in terms of its potential to (1) integrate safety with construction methods education; (2) transfer safety knowledge; (3) improve hazard identification ability; and (4) improve accessibility to safety information.

As illustrated in Fig. 7(b), the proposed VSES satisfied all its effectiveness criteria. Learners and educators recognized the system's potential to integrate safety with construction methods, improve hazard identification ability, and improve accessibility of safety information. Educators considered the VSES capable of sufficiently including complex details and realistic scenarios that would enhance learning.

Other effectiveness criteria considered the systems potential in facilitating active learning, outcome perception, and engaging and motivating learners, etc. Students were asked to provide any additional comments, feedback, and recommendations they had. The VSES was also found highly effective in supporting active learning by captivating and motivating students. Furthermore, it was observed to improve spatial cognition and effectively support outcome perception. These results indicate that the VSHES could be very effective in developing learners' hazard identification abilities, and safety knowledge.

Discussion

Based on the evaluation results, the VSES actively engaged and motivated learners' to facilitate the acquisition of safety knowledge and development of hazard identification abilities. Learners could virtually perceive the site hazards related to concrete works and reflect on the consequences of their actions. Contrary to initial expectations, a few participants considered the approach between neutral and effective in integrating safety with construction methods. This could be due to the small number of prototype scenarios as a result of the prohibitive costs of the full scale system development. The development and implementation of a full system to completely demonstrate the broader opportunities for scaled adoption was beyond the scope of this study. Further development of SHL, HIG, and SE scenarios will elucidate and further exemplify how safety could be incorporated, to contextually supplement and enhance construction methods education. Learners agreed that the proposed system would facilitate active learning, outcome perception, and student motivation as well as engagement. Educators raised concerns regarding the financial feasibility and development costs of the fully-functional VSES. The development of virtual contents and classification of safety information was also considered time-consuming and laborious. These development issues can be addressed through the utilization of BIM, virtual prototypes, and virtual contents from past construction projects. Such an approach

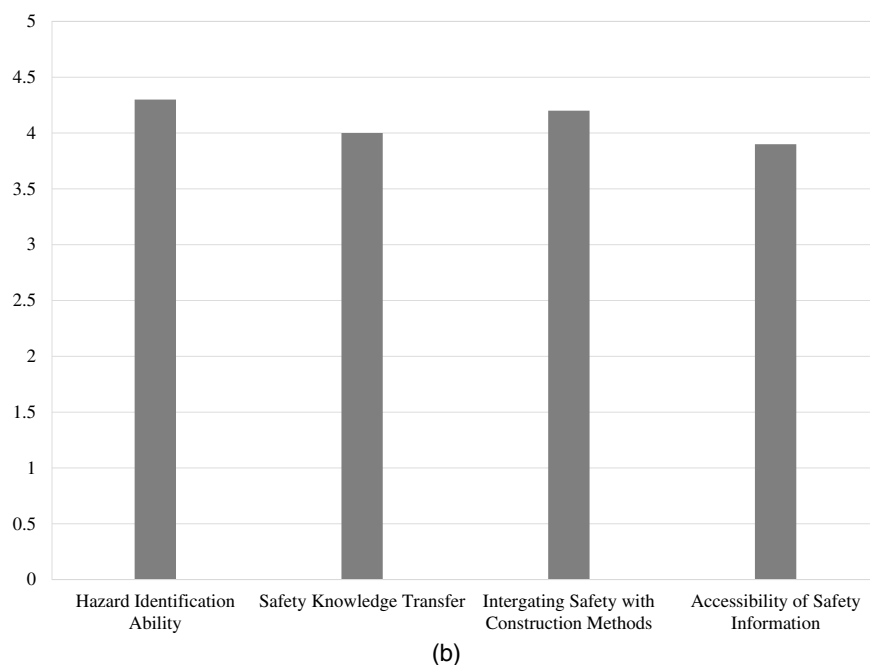
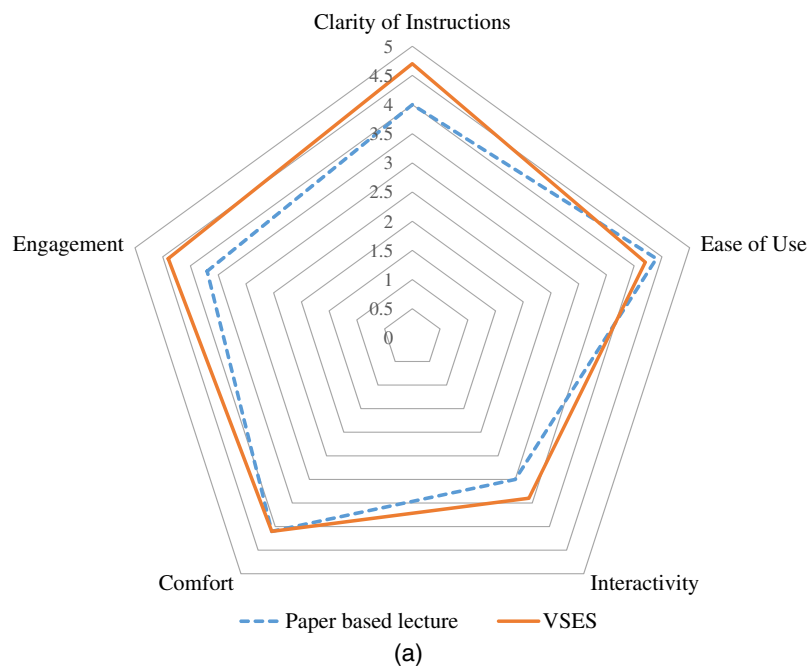


Fig. 7. (a) Interface evaluation; (b) VSES effectiveness evaluation

would relieve educators of the burden of virtual content modeling. Moreover, once virtual databases are established, their constituent scenarios may be reused repeatedly for years.

Conclusion

Nowadays, construction personnel are faced with unprecedented challenges and opportunities in meeting the needs of society; however, educational programs have not adequately prepared students for the safety demands of modern construction sites. In order to enhance tertiary construction education, this study developed a virtual safety-education system for university students, which incorporates safety into construction methods education by utilizing VR and smart devices to enable access to virtual contents through

textbook-based QR codes. A system framework was developed illustrating how safety education can be integrated with construction methods contents in existing curricula. The system comprises of three modules: (1) a safety and hazard lecture (SHL) module that enhanced traditional lecture materials with virtual jobsite scenarios; (2) a hazard identification game (HIG) module that gave students an opportunity to practice identifying and responding to hazards in a virtual game environment; and (3) the student evaluation and assessment (SEA) module, which utilizes virtual scenarios in testing learners safety knowledge and hazard identification abilities.

The preliminary feasibility of the approach was assessed and confirmed through system trials and interview with students, lecturers, and industry professionals. Results show that the VSES has the potential to integrate safety with construction methods education, improve learners' safety knowledge, and hazard identification

abilities. The next stages of the VSES development will involve matching safety rules, regulations, hazards, and accident cases with textbook sections. Subsequently the HIG will be developed with full interactivity to deliver more-compelling levels of sensory fidelity. Further evaluation of the VSES system would involve teaching a class using traditional paper-based and projector-based materials, and performing hands-on trials with the proposed systems SHL and HIG modules in another class with 30–40 students. Through a paper-based test, a performance-based comparison will then be implemented, assessing learners' scores prior to traditional safety education and the proposed VSES. Differences between the before and after education scores will be calculated, and the significance of the differences will be validated through statistical T-tests. Lastly, immediate and six-month safety knowledge retention levels will be evaluated.

The initial development, implementation, and evaluation of the VSES framework and prototype indicate that the proposed system can bring immense benefits to construction safety education by reliably representing the inherently dynamic nature of construction projects at the university level. Increasing institutional commitment and support will yield even greater outcome improvements for the VSES implementation. This study has shed light on how safety can be integrated into construction education using VR, mobile devices, and QR codes. Future studies will quantitatively measure the impacts of the VSES and adopt interactive building anatomy modeling (IBAM) for even more comprehensive building construction education not only for tertiary safety education, but for worker training as well.

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