APPLICATIONS OF VISUALISATION TECHNOLOGY IN CONSTRUCTION SAFETY TRAINING: A PRELIMINARY REVIEW

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The construction industry is a hazardous industry and characterised by high number of workplace injuries and fatalities. Research evidence indicates that risk factors such as a lack of trade knowledge and skills, inadequate understanding of risk controls, and low level of safety awareness can contribute to workplace accidents. This highlights the importance of training in assuring that workers competently perform work tasks by adhering to health and safety requirements. The conventional way of developing safety knowledge and compliant skills is to attend classroom-based training on safety procedures and related codes of practice. However, such a training approach has long been questioned about its effectiveness due to low level of engagement and lack of opportunities to practice in a real site scenario. Emerging visualisation technologies such as virtual reality (VR), augmented reality (AR) and gaming environments seem promising to overcome the limitations of traditional training approach. Researchers have attempted to develop various visualisation technology-enabled training systems or approaches to enhance training effectiveness. However, a systematic understanding of what and how visualisation technologies have been used to support safety training is missing. A study is being initiated to systematically review literature to examine the status of visualisation technology-enabled training approaches in construction. This paper reports the preliminary results from a pilot study. The results indicate that the application of visualisation technologies in safety training is still in the early stage. Existing applications primarily have focused on hazard identification and specific work tasks, but haven't considered broader contextual factors (e.g. construction types, training needs in project lifecycle), pedagogy (e.g. learning methods), learners' characteristics (e.g. experience, skills), etc. A four-dimensional framework is suggested in this study to provide directions for future research in applications of visualisation technologies in safety training.

Keywords: safety, training, visualisation technology, worker skills, review

INTRODUCTION

The construction industry has long been considered as a hazardous industry with alarming statistics of construction workplace injuries and fatalities recorded. For

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example, in Australia, the construction industry accounted for 9% of the Australian workforce but 10% of workers' compensation claims for injuries and diseases involving one or more weeks off work during 2012-2013 (Safe Work Australia, 2015). In addition, 153 worker fatalities were recorded in the Australian construction industry during 2013-2017, which accounted for 16% of total worker fatalities (Safe Work Australia, 2017). The construction industry has been identified as a priority industry by the Australian Work Health and Safety Strategy 2012-2022 for developing prevention strategies to reduce injury and fatality rates (Safe Work Australia, 2012).

Haslam *et al.,* (2005) analysed 100 construction accidents, and reported that the factor of worker capabilities (including knowledge/skills) was involved in 42% of the accidents. They further pointed out that underlying this analysis result is workers' inadequate safety knowledge as well as deficiencies with safety training. The development of effective training approaches to increase workers safety competence has been highlighted as an important strategy to prevent injuries and fatalities (Wilkins, 2011). The Australian Work Health and Safety Strategy has defined one of the national Action Areas as "Health and Safety Capabilities" and specified that work health and safety skills development should be integrated effectively into relevant education and training programs (Safe Work Australia, 2012).

Safety training has been conventionally provided in a classroom setting facilitated by a trainer with text-based or imaged-aided instructions. The classroom-based training is normally conducted in the form of lectures with the main purpose of disseminating safety-related information, e.g. safety policies, procedures, rules and code of practices. This conventional training approach has received many critiques regarding its' effectiveness. For example, Burke *et al.,* (2006) described the lecture form of training as passive and "least engaging" methods of safety training. There is little opportunity for workers to interact with practices and gain hands-on experience. Wilkins (2011) examined workers' perceptions of a classroom-based OSHA 10-Hour Construction Safety Training Course, and reported that many workers were dissatisfied about the course due to various reasons, including the difficulty in understanding training material, the irrelevance of training content to their work practices, and the incompetency of trainers who largely failed to address adult learning characteristics.

Emerging visualisation technologies, such as virtual reality (VR), augmented reality (AR), mixed reality (MR) and gaming environments, are gaining increasing attention from researchers regarding their potential to overcome the limitations associated with traditional training approach. Training approaches enabled by those visualisation technologies are highly engaging in nature, and emphasize behavioural modelling, e.g. observing a role model, modelling or practice, and assessment or feedback designed to modify behaviour (Burke *et al.,* 2006). These approaches also often involve hands-on demonstrations associated with behavioural simulations, which provides a highly participatory experience for trainees (Burke *et al.,* 2006). The practice-based learning potentially improves knowledge acquisition, retention, and training transfer.

Despite the existing efforts in designing technology facilitated training systems or approaches, so far there hasn't been a systematic understanding of what and how different visualisation technologies have been used in safety training, and what aspects can be further improved to achieve more effective training outcomes. A study is being initiated to systematically review literature to explore answers to those questions. This paper only reports preliminary results from a pilot study.

LITERATURE REVIEW

Visualisation technologies have gained applications in complex machinery operation training and complex procedural skills development. For instance, the risk of being crushed against overhead structures is ever present and therefore should never be overlooked. Several situations can lead to crushing, but operators have reported the lack of operational proficiency, i.e. dealing with complex panel functions and varied control suites, is a major problem (Hou *et al.,* 2017). This has aggravated the sophisticated nature of operating auxiliary equipment in line with the demands of large-scale complex asset maintenance projects such as mining equipment, liquefied natural gas facilities and power plants (Krasnyanskiy *et al.,* 2014). The substance of prior-task preparation and planning is placed on the integration of complex procedural training and human factors as they relate to improvement of cognitive skills as well as the deployment of advanced visualisation technologies to achieve better outcomes in, for example, the machine operation case. Training for the operation of increasingly complex machinery and complex procedural tasks using such machinery benefits from visualisation technologies and will expand into complex procedural support.

VR, AR and MR technologies have also been widely developed to generate interactive training settings and proved to be conducive to high-risk and inaccessible work environments (Ioannidis *et al.,* 2014). The shift from current in-class and equipment-based training to portable visualisation technologies is an innovation that allows training delivery onsite for workers and operators. The portability benefits afforded by visualisation paradigms integrated into training curriculums will assist asset companies with workers and operators located on widely dispersed sites to benefit from productivity gains. The significant benefits from moving away from complete immersion administered via costly, centralised high-fidelity interfaces has been acknowledged as beneficial in other sectors as well.

In addition, it is preferred that whatever actions that will be taken can be fully rehearsed in advance and/or well instructed during the task. Things such as task duration, workplace access and safety, ergonomic factors, if can be made known to the crew upfront, will be able to improve the crew's awareness to the task context. Site access and personnel evacuation problems have recently attracted significant research attention, resulting in diverse applications and optimisation solutions (Tsai *et al.,* 2012). The awareness of workspace contexts and uncertainties, if gained by human operators, would greatly reduce the probability of accidents while the task is in progress. AR and MR technologies that enable a visual and perceptive connection between a physical workspace and a virtual counterpart, can be leveraged to facilitate such awareness and fulfil safety considerations (Irizarry *et al.,* 2013).

Construction tasks normally involve multiple collaborative entities such as workforce, physical presence, schedule, information, materials, tools, equipment and assets. These tasks require high level manipulation skills, problem-solving strategies, hazard awareness and decision-making based on knowledge of occupational health and safety requirements. Studies prove that 35-45% of working time of taskforce is spent in looking for the right information, provided the common approach of information retrieval being paper-based drawings (Ruwanpura *et al.,* 2012). However, traditional presentations of work plans or drawings could be misinterpreted, imprecise or outdated. The digital visualisation of information contained within BIM can provide those on-site personnel with an improved understanding of task sequencing, which will reduce the incidence of quality and accuracy failures. Holding a tool or a work piece while looking for information could easily distract a technician from the work task he is undertaking, whereas AR and MR concepts can be leveraged to make information readily available and expedite asset tasks with efficiency and effectiveness guaranteed (Hou and Wang 2013). For example, information (retrieval and display) would be integrated with views of the work piece if the technician wears a head-mounted display (HMD).

AR technologies show the potential to support maintenance decision making and improve the human performance for technical maintenance tasks (Palmarini *et al.,* 2018). To increase the efficiency, operating savings and reliability of railway assets, Hall *et al.,* (2015) developed a tablet-based asset management platform which can overlay AR clues onto a view of the railways. The haptic features incorporated in this system involved AR graphics, VR video, as well as sensor-gathered sound and location data. When integrated with BIM technologies, tablet-based AR has the potential of providing asset managers with mobile access to their required asset information. On the other hand, a finer asset practice would need the practitioners to shed light on not only better AR/BIM interfaces, but also more streamlined asset management processes that support digital work manners (Gheisari and Irizarry 2016).

The various applications of visualisation technologies presented in the literature review provide implications for using those technologies in the construction industry. However, the utilisation of visualization technologies in construction skills training and particularly in safety training is not much prevailing comparing with that in other industries (Park and Kim, 2013). There is a need to examine the status and potential of visualisation technologies in supporting safety related training in construction.

RESEARCH METHOD

This pilot study was conducted with a small-scale literature review. The database of ScienceDirect was used to search a list of studies in relation to the application of visualisation technologies in safety related training in construction for the pilot study. This database was chosen because it contains many scientific and engineering journals that are relevant to the construction safety area. The predefined key words of ("virtual reality" OR "augmented reality" OR "mixed reality" OR "immersive environment") AND training AND construction AND safety were used to search relevant literature within the range of years 2000-2019. The searching results were restricted to those publications that have the predefined keywords appear in publication title, abstract or author-specified keywords. A total of 13 publications were sourced through the searching process. A screening process indicated that two publications were literature review papers, one publication discussed how to use VR to capture building users' performance, while another publication discussed how to use tracking system and VR to analyse workers' postures while working and categorised work tasks into ergonomic or non-ergonomic categories. These four papers were excluded from further review and analysis. Table 1 lists the summary information of these papers.

Table 1: Summary of the publications sourced for analysis

Authors (Year)	Journal title	Country of study
Azhar (2017)	Procedia Engineering	USA
Cheng and Teizer (2013)	Automation in Construction	USA
Goulding *et al.*, (2012)	Advanced Engineering Informatics	UK
Hou *et al.*, (2017)	Automation in Construction	Australia
Kim *et al.*, (2017)	Automation in Construction	Korea
Li *et al.*, (2012)	Automation in Construction	Hong Kong
Park and Kim (2013)	Automation in Construction	Korea
Perlman *et al.*, (2014)	Safety Science	Israel
Teizer *et al.*, (2013)	Automation in Construction	USA

The remaining nine publications were subject to a critical review and theme coding by researchers. The main purpose of the literature analysis was to explore: 1) what and how visualisation technologies have been applied in safety-related training in the construction industry; 2) what are the underlying mechanisms through which visualisation technologies improve the effectiveness of training; 3) what issues and limitations are associated with the designs of training approaches.

RESULTS

Table 2 lists the analysis results for the nine publications. Due to the length limitation of the paper, only part of the results is summarised using the table while other results will be described in paragraphs. The results indicate that various technologies, including VR, AR, BIM, tracking technologies and game engines, have been utilised to support training. The application contexts ranged from risk/hazard identification (4 cases), assessing training processes (2 cases), training complex procedural tasks (1 case), warning workers of hazardous situations (1 case), and understanding safety implications of decisions and actions (1 case). The mechanisms underlying those training approaches are primarily related to the abilities of visualisation technologies in capturing and visualising real-world scenarios, providing rich information about site conditions and environment, and enabling workers to practice tasks or understand hazards inherent in work activities in a hazard-free environment.

All the publications also included an assessment/evaluation section to assess/evaluate the applicability of training systems or approaches. Most of the studies used the method of experiment (5 cases) in a controlled environment conducted with either trainees, professionals or graduate students, while the others (4 cases) invited participants to provide feedback or opinions. Almost all the publications reported promising or positive assessment/evaluation outcomes.

DISCUSSION

Despite the range of years for literature searching was specified to be almost two decades (i.e. 2000-2019), only nine publications were sourced from the databased relevant to the application of visualisation technologies in supporting safety training in construction. This, to certain extent, implies that the utilisation of visualisation technologies in safety training is still in the developmental stage, and there is great potential for further research into this area to achieve improved training outcomes. The application contexts for visualisation technologies primarily focused on improving individual capability in risk/hazard identification through virtual environments.

Table 2: Analysis results for the literature

Study	Technology	Safety aspect	Underlying mechanism
Azhar (2017)	Immersive virtual environments (Oculus Rift) - a light weight headset Convert a BIM model into VR environment	Hazards identification on construction site: • Unsafe use of forklifts • Inadequate fall protection • Electrical hazards • Falling objects • Tripping hazards	The project team members used the VR headset to view the created hazardous scenarios and provided their feedback.
Cheng and Teizer (2013)	Real-time location tracking sensors (Ultra-Wideband tags) and VR	Monitoring safety and activities among ironworker apprentices and trainees	Visualised training sessions by tracking real-time data; Close-call incidents were identified and converted to VR and replayed to the trainees and trainers; Provided feedback on mitigation
Goulding *et al.*, (2012)	Interactive VR environment	Safety implications of decision makings for construction offsite production	Developed scenario-based learning from a real site and visualised it in VR; Trainees made decisions and took actions based on different site scenarios; Trainees understood how different decisions/actions led to different consequences
Hou *et al.*, (2017)	Mixed reality (with AR and VR)	Procedural skills training in operating and maintaining oil and gas facilities	Trainees virtually interacted with a scenario tailored for specific task requirements and rehearses the task procedures; Such training systems could enhance trainees' visual-spatial, psychomotor and cognitive, and kinaesthetic capabilities
Kim *et al.*, (2017)	An image-based safety assessment system capturing safety information, which is visualised using AR in a wearable device	Construction site: to reduce struck-by accidents	The vision-based hazardous avoidance system helped workers to instinctively recognise hazardous situations and take proactive measures to avoid danger
Li *et al.*, (2012)	Game engine technology (Unity 3D) enabled visual safety assessment system (VSAS)	Workers' hazard identification and safety assessment relating to PPE	The virtual training approach provided rich information on site conditions, work behaviours and construction methods, and provides meaningful ways of assessment
Park and Kim (2013)	Safety management and visualization system (SMVS) that integrates BIM, location tracking, AR, and game technologies	Risk identification, workers' capacity of risk recognition, communication between managers and workers	The system as a safety education tool enabled worker to pre-experience activity-specific safety risks; improved safety communication between managers and workers
Perlman *et al.*, (2014)	Virtual reality	Hazard identification	VR enabled individuals to be present within hazardous conditions and identify workplace hazards
Teizer *et al.*, (2013)	Tracking system with Ultra-Wideband (UWB) location tracking technology	Safety performance in steel-erection training sessions	Visualising the training session by tracking real-time data helped to review the training process, assess the effectiveness of the training program and obtain feedback for improvement

However, apart from being able to recognise potential hazards in the work environment, construction workers also need to understand risks associated with their work tasks and perform the tasks adhering to safety requirements. A construction project normally involves a large amount of work tasks and trade activities. This raises a concern that what tasks and activities are more suitable to be trained with visualization technologies, or to which extent virtualised training content can be generally used in multiple work tasks or activities. Future research can potentially develop a taxonomy identifying the applicability of different training approaches for different construction work tasks by considering the characteristics of work tasks.

The research results indicate that visualisation technologies are not only used for training purpose, but also used to assess the effectiveness of training through virtualising and then reviewing training sessions. The review process provides valuable feedback in terms of what improvements are required from trainees in their learning process and how trainers can better facilitate the training process. Future research can extend the application to assess another critical element of training, i.e. training transfer, which is defined the extent to which trainees apply the learned skills and knowledge in their actual work. Training does not result in improved safety and productivity performance if trainees do not transfer acquired skills and knowledge into work (Baldwin and Ford, 1988).

It seems that none of the studies has considered user/human factors when designing the virtualised training systems, such as the levels of skills (i.e. entry, advanced, and experienced), the level of familiarity with technologies and individual learning styles. Apart from considering technical issues (e.g. compatibility between technologies, the performance of display car), research may also need to consider personal factors to enhance the human-technology interactions.

Most of the assessment or evaluation processes in the publications were not robust enough. For example, some studies invited graduate students to participate in experiments in controlled environments, some did not involve a control group to compare results, while some invited professionals and workers to have a trail experience and provide qualitative feedback. It can be difficult to ascertain the real effectiveness of those training systems or approaches with such evaluation settings. Also, the participants involved in the evaluation can be different from actual trainees in terms of experience, skills, psychological factors, etc.

Although there is an abundance of safety training programs available in construction, there has been little investigation into the effectiveness of such programs (Tackett *et al.,* 2006). In the course of reviewing the literature on how visualisation technologies (e.g. VR and AR) may help to improve the quality of construction safety training comparing with the traditional classroom training, we reached a similar conclusion to Tackett *et al.,* (2006). The effectiveness of visualisation technologies' application in safety training hasn't been systematically evaluated against its learning outcomes. In addition, most of the VR and AR applications in safety training are limited to a single construction site with the main focus on enhancing hazard identification and disregards the possible variations on training needs in project life cycle, job types and human factors. To address these shortcomings, we developed the following framework based on the four-dimensional model of De Freitas and Neumann (2009) for future studies on the topic (Figure 1).

Drawing from the above framework in Figure 1, the application of visualisation technologies in safety training needs to firstly consider what people need to learn (context), how they learn it (Pedagogy), when they learn it (Learner), and where they learn it (Representation). Taking "job types" under context for example, it is likely that iron workers need different safety training content compared to crane operators on the site.

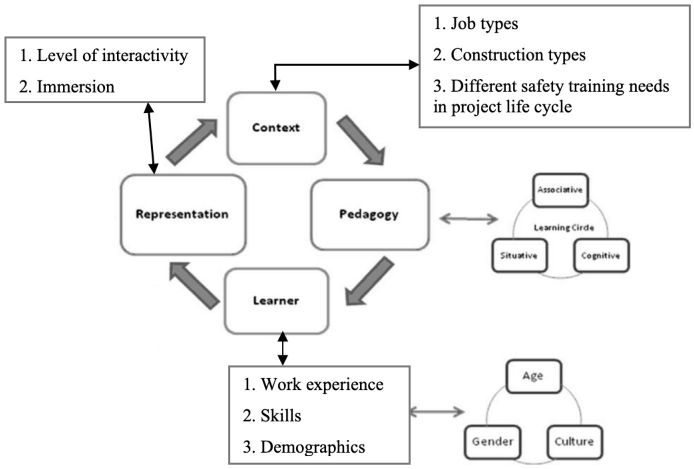

Figure 1: The four-dimensional framework

Different training content may require using different pedagogical methods: 1) Situative refers to supporting communities of practice; 2) Cognitive refers to building upon experience and reflection; and 3) Associative refers to giving immediate feedback. Different pedagogical methods will affect learners' experience. Based on learner's characteristics such as age, work experience and skills, the representation of visualisation technologies such as the level of interactivity and virtual reality could be vastly different. Finally, the effectiveness of the representation of visualisation technologies should be evaluated against the context.

CONCLUSION

This paper reports the preliminary findings from a pilot study using literature review. A literature searching was performed in the database of ScienceDirect within the range of years 2000-2019. Only nine studies were identified from this literature searching, indicating that the application of visualisation technologies in safety training is still in the early developmental stage. A further analysis of the literature indicates that existing applications of visualisation technologies have mainly focused on hazard identification and a few specific work tasks. Given a large amount of work tasks and trade activities involved in a construction project, it is unclear about what work tasks and activities are more suitable to be trained with visualisation technologies, or to which extent virtualised training content can be applied in multiple work tasks or activities. In addition, the development of visualisation technologies has not considered broader contextual factors (e.g. different work types, different training needs), pedagogy (e.g. theory of learning), and learners' characteristics (e.g. experience, skills), etc. This gap has led to the suggestion of a four-dimensional framework in this paper to provide directions for future research in application of visualisation technologies in safety training. A limitation associated with this paper is that only one database was used for the literature searching in this pilot study. A broader and more comprehensive literature review will be conducted to further understand the application of visualisation technologies in safety related training in future.

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