Automation in Construction 86 (2018) 150–162

Contents lists available at ScienceDirect

Automation in Construction

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

A critical review of virtual and augmented reality (VR/AR) applications in construction safety

Xiao Li[a], Wen Yi[b], Hung-Lin Chi[a], Xiangyu Wang[c,d,*], Albert P.C. Chan[a]

[a] Department of Building and Real Estate; The Hong Kong Polytechnic University, Hong Kong, China
[b] School of Engineering and Advanced Technology, College of Sciences, Massey University, New Zealand
[c] The Australasian Joint Research Centre for Building Information Modelling, School of Built Environment, Curtin University, Perth, Australia
[d] The International Scholar, Department of Housing and Interior Design, Kyung Hee University, South Korea

ARTICLE INFO

Keywords:
Virtual reality
Augmented reality
Construction
Safety
Review

ABSTRACT

Construction is a high hazard industry which involves many factors that are potentially dangerous to workers. Safety has always been advocated by many construction companies, and they have been working hard to make sure their employees are protected from fatalities and injuries. With the advent of Virtual and Augmented Reality (VR/AR), there has been a witnessed trend of capitalizing on sophisticated immersive VR/AR applications to create forgiving environments for visualizing complex workplace situations, building up risk-preventive knowledge and undergoing training. To better understand the state-of-the-art of VR/AR applications in construction safety (VR/AR-CS) and from which to uncover the related issues and propose possible improvements, this paper starts with a review and synthesis of research evidence for several VR/AR prototypes, products and the related training and evaluation paradigms. Predicated upon a wide range of well-acknowledged scholarly journals, this paper comes up with a generic taxonomy consisting of VR/AR technology characteristics, application domains, safety scenarios and evaluation methods. According to this taxonomy, a number of technical features and types that could be implemented in the context of construction safety enhancement are derived and further elaborated, while significant application domains and trends regarding the VR/AR-CS research are generalized, i.e., hazards recognition and identification, safety training and education, safety instruction and inspection, and so on. Last but not least, this study sets forth a list of gaps derived from the in-depth review and comes up with the prospective research works. It is envisioned that the outcomes of this paper could assist both researchers and industrial practitioners with appreciating the research and practice frontier of VR/AR-CS and soliciting the latest VR/AR applications.

1. Introduction

Construction is a large, dynamic and complex sector that offers a large number of employment opportunities for millions of people worldwide [1]. However, fatal accidents in the construction industry tend to be higher than other sectors [2], for a long run, such a phenomenon has aroused a lot of safety concerns and discussions. Safety management, a method of manipulating on-site safety policies, procedures, and practices relating to a construction project, is one of the most frequently leveraged techniques to regulate construction activities and control risks [3]. Previous studies revealed that most accidents associated with construction undertakings were attributed to a lack of proactive and preventive measures such as workforce training, risk source identification and control, safety awareness and education, and so forth [4]. On the other hand, how effective these measures could work is subject to how much job-site knowledge could be solicited and how efficiently the knowledge could be absorbed [5,6]. To this end, information visualization techniques such as Building Information Modeling (BIM), Virtual Reality (VR) Augmented Reality (AR), as well as other game engine-based Mixed Reality (MR) techniques, have been delved into to advance the current safety management practices [7–10].

A long-established climate that safety is tied up with management has placed many construction firms and researchers' primary focus on cultural intervention, uptake of safety behaviors, organizational ideologies, espoused and enacted policies, communication and induction, and etc. [11,12]. Meanwhile, a quick look through into VR/AR-CS publications helps identify that VR/AR technologies have been probed and tentatively implemented in various safety enhancement areas, such

* Corresponding author.
E-mail addresses: shell.x.li@connect.polyu.hk (X. Li), W.Yi1@massey.ac.nz (W. Yi), hung-lin.chi@polyu.edu.hk (H.-L. Chi), Xiangyu.Wang@curtin.edu.au (X. Wang), albert.chan@polyu.edu.hk (A.P.C. Chan).

https://doi.org/10.1016/j.autcon.2017.11.003
Received 29 July 2016; Received in revised form 9 October 2017; Accepted 3 November 2017
Available online 20 November 2017
0926-5805/

as risks identification, workforce training, skill transfer, ergonomics, and so on. Most studies have rationalized the development of a vast variety of VR/AR-CS systems for a safety enhancement purpose, and some studies have made efforts to summarize the VR/AR-CS. For example, Bhoir and Esmaeili [13] conduct an in-depth literature review to investigate the prevailing adoption rate of virtual reality environment to train workers regarding safety issues. And Guo et al. [14] examine the application of visualization technologies in construction safety and find that visualization technology can efficiently improve the safety training, facilitate job hazard area identification and accident prevention in a visual, interactive and cooperative way. However, they loosely compare how effectively these tailored technologies and systems, particularly for augmented reality and virtual reality, could be utilized to facilitate construction safety considering the disparity of evaluation method, technology characteristics, project types, scales, work complexity and other factors. Meanwhile, because the VR/AR-CS literature is found overwhelmingly diverse and vast, academia and industry may not be acutely aware of the authentic limitations and gaps in this area. Integration and classification of the reported literature within the VR/AR-CS domain may help them to gain a better understanding of the state-of-the-art and the related challenges. To cater to the industrial demands, additionally, it is also essential to have the most appropriate VR/AR devices, applications, systems, safety enhancement mechanisms and evaluation methodologies suggested. Therefore, the aims of this review are to address the aforementioned limitations and gaps through coming up with the most significant body of knowledge of VR/AR-CS and to drive the prospective research directions up to the most valuable and critical areas that the industrial and academic communities are adhering to.

2. An overview of VR/AR technologies and peripherals

Virtual reality (VR) simulation is to generate immersive environments from which users can experience unique insights into the way the real world works [15,16]. The concept of VR was brought up over fifty years ago when the first immersive human-computer interaction (HCI) mock-up named “Man-Machine Graphical Communication System” was invented [17]. The formal term of VR was put up in 1989 [18]. Since then, several taxonomies have been raised by scholars to expound where a rigorous VR concept should stay from along the continuum of reality to virtuality (RV). For example, Milgram's taxonomy (Milgram and Colquhoun, 1994) shown in Fig. 1 defines four levels of RV experience based upon the degree of blending that different electronic display systems can achieve; Benford's taxonomy [19] shown in Fig. 2 classifies four spaces according to the extent to which a group of users can access virtual objects from their local space and the extent to which a space is either synthetic or is based on the physical world. VR attempts to replace a user's perception of the surrounding world with a computer-generated artificial 3D environment. And such virtual 3D environment is not necessary to be established based on a real one. In the RV continuum based on Milgram's taxonomy, VR represents effort in creating a virtual environment (VE) with visual and immersive aids to let users feeling a “real” sensation. However, it can only provide a limited level of ‘realism’ due to a lack of sensory feedback to accommodate for perceptual and cognitive viewpoints [20]. As an emerging technology, AR integrates images of virtual objects into a real world. By inserting the virtually simulated prototypes into the real world and

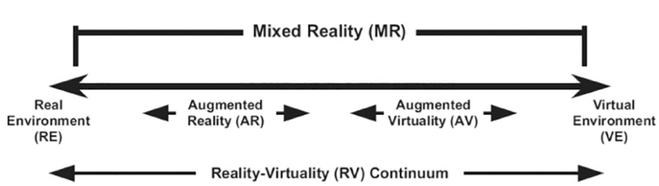

Fig. 1. Reality-virtuality (RV) Continuum [87].

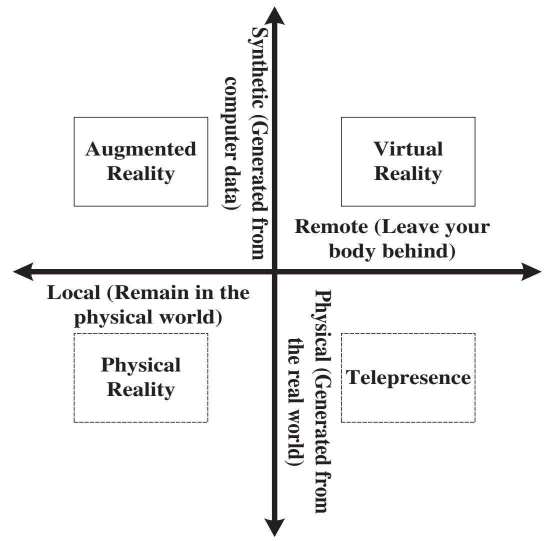

Fig. 2. Classification of Shared Spaces According to Transportation and Artificiality (adapted from [19]).

creating an augmented scene, AR technology could satisfy the goal of enhancing a person's perception of a virtual prototyping with real entities. This gives a virtual world an ameliorated connection to the real world while maintaining the flexibility of the virtual world [21]. In sum, the rigorous classification defined for VR and AR in this research is based on whether or not the visual sensations from the real world get to involve regardless of the establishment of immersion or the mechanisms of the display. While there is a blending of reality and virtuality, it can always be referred to Mixed Reality (MR) as a collective term. Such examples include a VR generated virtual environment fully superimposed on its related physical world, or the wide range of AR applications. In particular, AR, within the continuum of MR, generates an RV blended environment where the most of the visual sensation comes from the real world, and the virtual elements contributed less. The percentages of reality and virtuality can be reverted for augmented virtuality (AV) which is not discussed in this paper.

Ever since the first mature wearable VR/AR device (i.e., Google Glass, Forte VFX1) on the market, the reality of mobile VR/AR devices seems to be inevitable and have the potential to enrich the way information is accessed and presented. Technology developers (including hardware and software) from around the world have been trying to work with big brand marketers to build more tangible and auditory VR/AR solutions to deliver the best solutions matching clients' requirements and objectives (Fig. 3). Instead of just being able to interact with 3D contents in a pure computer-generated environment, users nowadays are capable of realizing a highly immersive, holistic and realistic experience underpinned by synthesized digital and physical world information presented using more sophisticated software and hardware. As shown in Fig.4, the paramount for the sensation of immersion into VR/AR are a high frame rate (at least 95 fps) and low latency. Furthermore, a pixel persistence lower than 3 ms could prevent users feel sick when moving their head around. Nowadays, the gap between the real world and its digital counterparts is becoming narrower. The tremendous potential that VR/AR could lead to a number of important changes in human life and activity has been witnessed from a wide range of application areas such as education and training [22], engineering [23], architectural and urban design [24], heritage and archaeology [25], medical science [26], entertainment [27] and so forth. In order to understand the frontier of VR/AR technologies from a broad range of application areas and uncover the possibilities of using VR/AR in construction safety, this paper provides a thorough review of mainstream literature published between 2000 and 2017. The selected articles were classified according to a four-level taxonomy: (1) technology

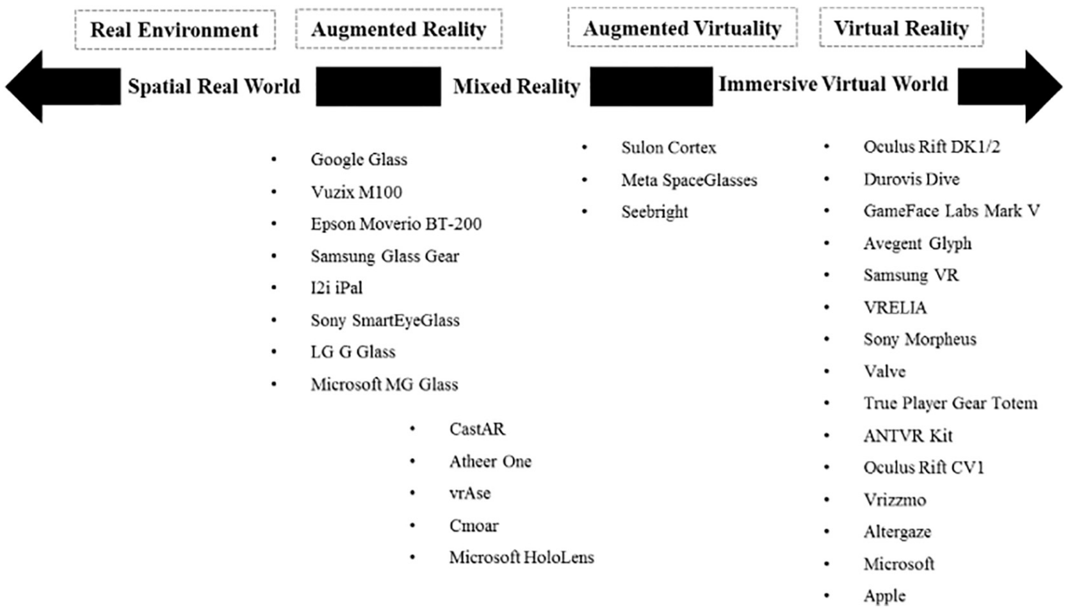

Fig. 3. Off-the-shelf VR/AR Systems and Technology Providers.

characteristics; (2) application domains; (3) safety enhancement mechanisms; and (4) safety assessment and evaluation. The rigorous classification of the literature could provide a critical framework for analysis and summarization of the state-of-the-art work in AR/VR-CS research. This study sets forth a list of gaps derived from the in-depth review and comes up with the prospective research works. These works look to assist both researchers and industrial practitioners with appreciating the research and practice frontier of VR/AR-CS and soliciting the latest VR/AR applications.

3. Review methodology

This research leverages the content analysis-based review method [28]. This method has been a well-recognized method for reviewing and synthesizing literature and rationalizing outcomes, and been widely applied in the research field of engineering/construction management [29,30]. Scopus and ISI Web of Science, the abstract and citation database of peer-reviewed literature, were used to select a number of first-tier articles that are related to VR/AR-CS, from the authoritative and well-acknowledged scholarly journals in selected areas such as engineering/construction management, science, and technology, safety, human factors, etc. The selection criteria are as follows:

(1) The selected journals should be retrieved from the Science Citation Index (SCI)-Expanded database or Engineering Index (EI) Compendex database because they have indexed more than 6500 notable and significant journals from more than 150 disciplines.
(2) The selected journals should have significant impacts on the targeted areas, which could be reflected from the indexes of citations or H-index. Book reviews, editorials, and paper in conference proceedings were eliminated. This is to ensure that all retrieved papers could be investigated using an identical analytical construct in terms of research aims and methodologies.

To achieve a target and structured review towards the literature (from 2000 to 2017), a two-stage review method is presented. In stage 1, an exhaustive search was carried out using the Scopus, Google

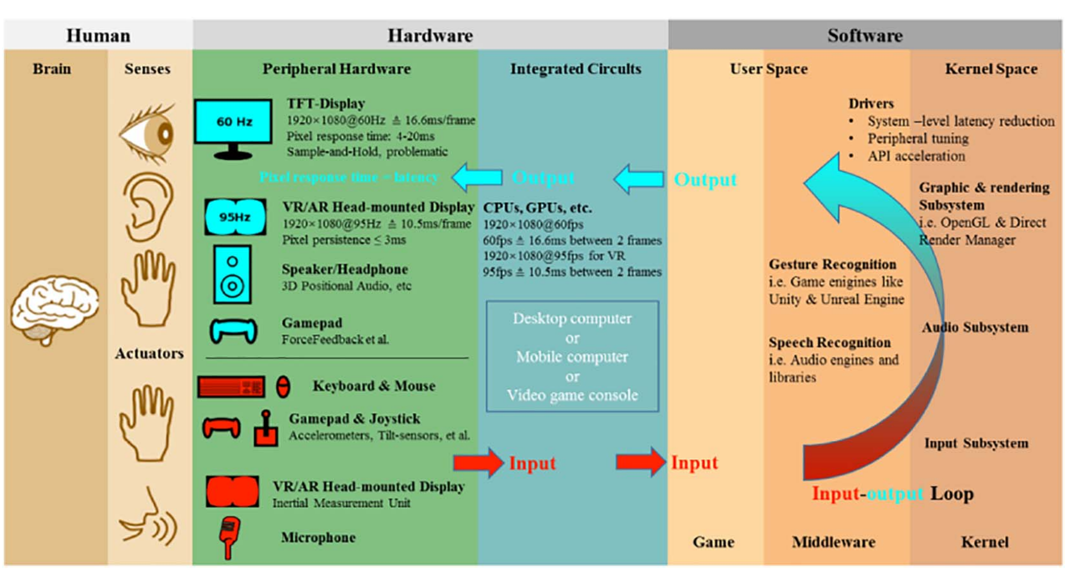

Fig. 4. VR/AR Hardware and Software Diagram.

Scholar and Web of Science search engines. Several keywords such as VR, AR, mixed reality, virtual prototyping, gaming technology, immersive, interactive, construction, safety, etc. were attempted so that the search could cover a broad range of related disciplines. This round of search identified 246 most related articles from the below-listed journals:

- Automation in Construction (AIC),
- Journal of Computing in Civil Engineering (JCCE),
- Advanced Engineering Informatics (AEI),
- Construction Management and Economics (CME),
- Journal of Construction Engineering and Management (JCEM),
- Applied Ergonomics (AE),
- Ergonomics (EG),
- Safety Science (SS),
- Accident Analysis and Prevention (AA&P)
- Journal of Information Technology in Construction (ITCon)

Publications which do not comprise the above-mentioned keywords in their titles or abstracts were screened out in stage 2, and the less relevant and irrelevant papers after a brief visual examination of the content of the article, leaving a total of 90 publications for further analysis. The two-stage search may not guarantee a comprehensive coverage of the papers that are worth reviewing. However, such an approach suffices for providing with a considerable amount of significant state-of-the-art works, from which the study could generalize findings and recommend future works.

4. Justification of publication quantity and contribution

Since the emergence of the first VR/AR-CS publication in 2000, the number of yearly publications remained at around 1.5 and was not observed a noticeable increase until 2008. From 2008, a significant increase of publications was witnessed, featuring an average amount of 8 papers per year till 2017 (Fig. 5). Among these journals, three construction-technology-themed journals (namely, AIC, JCCE and ITCon) are observed the highest amounts of publications, i.e., 30 for AIC, 12 for JCCE, 8 for ITCon, 7 for JCEM, 7 for AEI, 5 for ITCon, 3 for SS and 3 for EG. The number of VR/AR-CS papers published in AIC was thereto considerably greater than any other selected journals, resulting in the most contributions of this specific journal to VR/AR-CS studies.

The difference of publication quantities among various countries may imply the extent to which research commitment and value are observed in these countries. The countries of origin of VR/AR-CS publication as shown in Fig.6 are listed alongside the factors of publication quantity. American authors and research institutions leading the papers contributed 30 papers and thereby scored the highest. A reasonable justification would be U.S. has been leading the research and technology advancement in visualization and informatics for years.

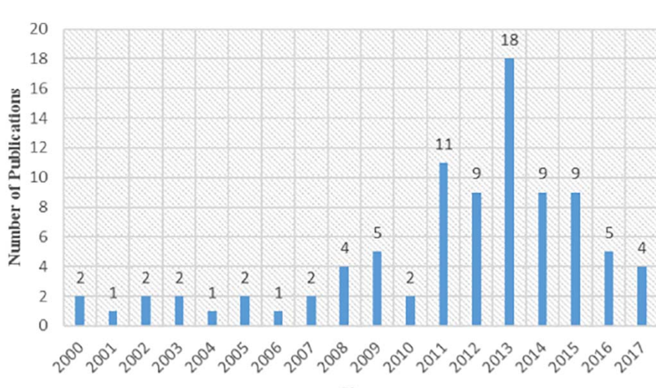

Fig. 5. Number of VR/AR-CS Papers Published in the Selected Journals.

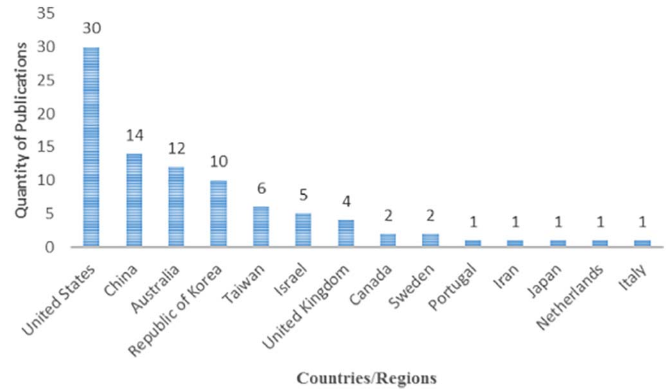

Fig. 6. Number of VR/AR-CS papers distributed in the different countries/regions.

Behind the US, China takes up the second position, leading the rest of the second-most productive countries/regions such as Australia, Republic of Korea, and Taiwan. As the total amount of VR/AR-CS papers from these five key contributors account for 80% of the total publication scale (72 of 90), the contributions to VR/AR-CS research are thereby perceived as more significant than the remaining contributors. The development of VR/AR-CS research also indicates that the degree of attention to construction productivity, safety, technological innovations and reforms within these countries.

5. Implementation of critical review

As the review deals with numerous papers, it is important for the methodology to be predicated upon a rational taxonomy that can help direct the review focus and elicit the valuable findings into the area of research. This paper presents a review taxonomy consolidated by four specifications, namely, VR/AR technology characteristics incorporating input and output; VR/AR application domains in safety management; safety enhancement mechanisms; and safety assessment and evaluation (Fig.7). Designing proper VR/AR technologies for safety enhancement is not easy, and always involves a number of technology trade-offs. It's a fine balancing act. A more immersive user experience requires more interactive human-machine interfacing, necessitating the use of more advanced hard and software with more powerful algorithms working at a higher load. A glimpse of VR/AR technology characteristics could understand the opportunities and challenges that the off-the-shelf VR/AR applications still need to catch up or stand a chance of overcoming. By looking into the VR/AR application aspects and safety enhancement mechanisms, we could understand how effectively the reviewed applications could improve the safety outcomes of real construction projects, and how effectively the VR/AR experiences could enable users to visualize and recognize complex workplace situations, from which the knowledge of procedures and skills could be built up, and tasks in a safe and forgiving environment be carried out. Safety enhancement mechanisms, when addressed from the perspectives of ergonomics, psychology, educational pedagogy, human perception, and cognition, may elicit knowledge about how VR/AR-based safety training programs can offer a more pertinent working environment where users can effectively rehearse hazardous factors and ultimately promote the abilities for hazard cognition and prevention. The analysis of a broad spectrum of evaluation methods allows us to extract general findings from the review work, which in turn could be applied to refine the existing systems, design new systems, and generate guidelines for formulating the best safety enhancement paradigms.

5.1. Classification of technology characteristics and major challenges

5.1.1. State-of-the-art studies of VR/AR technologies

A VR/AR system is typically referred to hardware components,

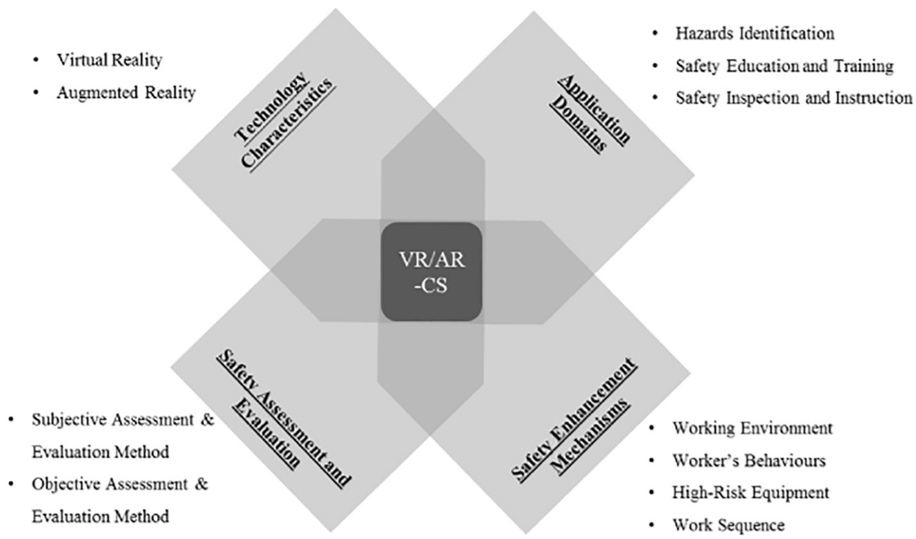

Fig. 7. VR/AR-CS review taxonomy.

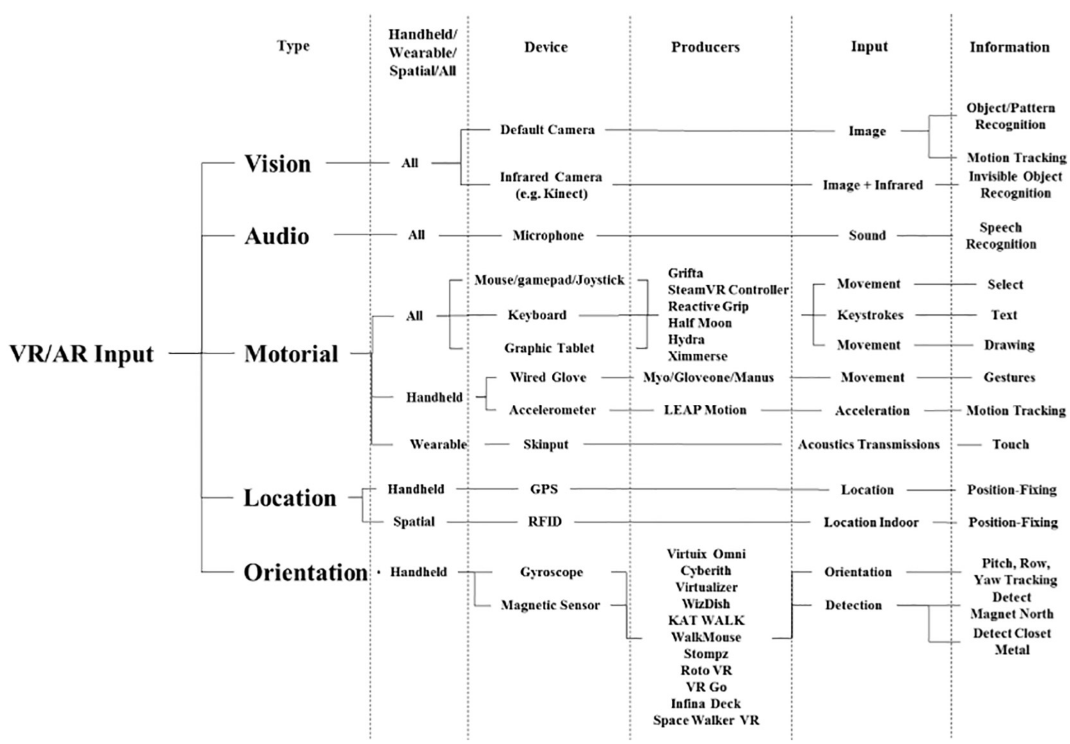

Fig. 8. A Taxonomy of VR/AR Input Devices.

software, and algorithms. Hardware incorporates a processor, display, sensors and input/output devices, and software and algorithms refer to the main measures regarding how realistically a VR/AR scenario can be achieved, the input devices (taxonomy is created as Fig. 8) are the means by which the user interacts with the virtual world [31]. They send signals to the system about the action of the user, so as to provide appropriate reactions back to the user through the output devices (taxonomy is created as Fig. 9) in real time [32]. The computer with VR/AR engine handles the interaction with users and serves as an interface with the Input/Output (I/O) devices. For example, the more processing power and a powerful graphics accelerator or distributed computer systems interconnected through high-speed communication network could make the calculating and generate graphical models, object rendering, lighting, mapping, texturing, simulation and display in real-time [15]. VR/AR system software is a collection of tools and software for designing, developing and maintaining augmented or virtual environments and the database where the information is stored [33]. The VR/AR system could be configured or selected according to the requirement of the application in construction safety to achieve the different level of immersion or interaction [34].

According to the level of immersion derived from a varied combination of hardware and software configurations, the reviewed articles can be further divided into seven categories (Table 1). Least-immersive VR systems, also called Desktop VR system, Fish tank or Window on World system is the least immersive and least expensive of the VR systems, as it requires the least sophisticated components [35]. Its application areas in VR/AR-CS include education and training. Semi-Immersive VR system, also called hybrid systems, provides a high level of immersion while keeping the simplicity of the desktop VR or utilizing some physical model. An example of such system includes the CAVE (Cave Automatic Virtual Environment), and an application is the crane simulator [36]. Interestingly, full-immersive VR system takes an only

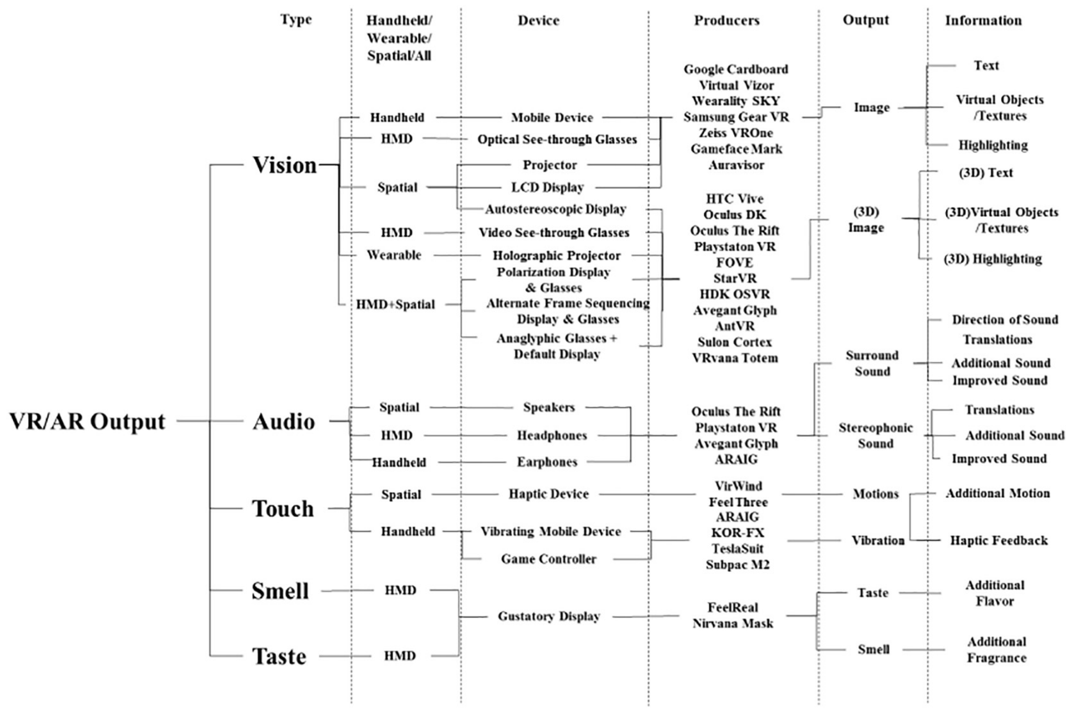

Fig. 9. A Taxonomy of VR/AR Output Devices.

Table 1
A taxonomy of VR/AR systems according to the technology characteristics.

Classification criteria	Number of articles	Relative percentage of subject	Global percentage of all subject
Technology characteristics	90	100%	94.50%
Least-immersive VR	16	17.80%	18.80%
Semi-immersive VR	22	24.40%	25.90%
Immersive VR	6	6.70%	7.10%
Tangible AR	32	35.60%	37.60%
Collaborative AR	4	4.50%	4.70%
Distributed AR/VR	5	5.50%	5.90%
Other VR/AR	5		

proportion of 6.7% in VR/AR-CS, on the other hand, it is the most expensive and gives the highest level of immersion to give the user the feeling of being part of the virtual environment. One of its applications is in virtual walk-through of the construction site to recognize hazards [6]. The tangible AR system (account for 32%) is widely applied in VR/AR-CS particular in the process of inspection and instruction, which objects in the real world are used as AR interface elements, and their manipulation is used for interacting with virtual contents [37]. 4.5% and 5.5% of the VR/AR-CS studies focused on collaborative AR and distributed-VR/AR respectively. This number is reasonable and not surprising, considering these two technology categories are emerging in construction safety. In collaborative AR, users share space that contains both real and virtual objects [38]. In this way, the interactions are not only between a user and the AR system but are also among users. Distributed-VR/AR also called Networked-VR/AR, which exists as a result of rapid development of the internet. Its goal is to remove the problem of distance, allowing people from many different locations to participate and interact in the same virtual world through the help of the internet and other networks [39].

5.1.2. Challenges faced by technologies

In order to operate with visualized objects for improving construction safety management, it is necessary to create an efficient system for the user. For achieving such system, the actions as: scaling; navigating in visualized 3D space; selecting sub-spaces, objects, groups of visual elements (flow/path elements) and views; manipulating and placing; planning routes of view; generating, extracting and collecting data (based on the reviewed visualized data) should be realized. However, some significant challenges are still existing as the following:

- How to classify the input information (see Fig. 8) and output information (see Fig. 9) at various levels for different application requirements in construction safety?
- How to enhance the connectivity and interoperability of VR/AR systems with input information (see Fig.8) which collected by other information and communication technology(ICT)tools to reduce the latency?
- How to select the customized hardware (i.e., user-friendly interfaces) and software (customized and reusable contents, models and databases) to achieve multi-level requirements of VR/AR-CS systems?

5.2. Classification of application domains and major challenges

The typical applications of VR/AR-based construction safety management consist of safety planning, safety training and education, and safety inspection [4]. Safety planning gets high priority for safety management teams to identify the hazards or risks before actual work at the site [40]. Safety training and education are aimed to make novices understand the safety concerns in terms of work location,type of work, type of risk, and behavior risk exposure. The safety inspection is for construction inspector to check unsafe conditions and deliver the risk information to workers. This study will take the three management focus as the main application domains to give a systematic analysis.

5.2.1. State-of-the-art studies of VR/AR applications

5.2.1.1. Hazard identification. Hazard identification (or risk recognition) relies on the capability of safety planning team in sensing, analyzing, and extracting potential dangers during the construction [41]. Based on the site situation evaluation, they could make practical plans such as safety facilities selection, education requirement, working sequence adjustment, and safety patrol [4]. Traditional methods of hazard identification focused on desktop concepts and conventional sources on the drawings, accident cases, and heuristic knowledge are being used to prepare prevention measures against expected safety risks through project meetings [23]. Such approaches are hard to directly catch the precautions from construction participants and reflect the real field (i.e., dynamic and unpredictable) circumstances [42]. To enhance participants' immersive and interactive experience, modeling and visualization of VR environments for hazard identification emerged [36,43].

By far several systems for identifying hazards have been developed, including Design-for-Safety-Process (DFSP) system [43], System for Augmented Virtuality Environments (SAVEs) [42], Cave Automatic Virtual Environments (CAVEs) [36], Visualized Safety Management System (VSMS) [4]. These systems are designed for designers, site workers with different trades, students, safety managers respectively. The comparative studies and experiments have been conducted in these systems. Results indicated that most users in the virtual environment assessed higher risk levels and identified more hazards than the ones who studied photographs and documents [44]. Meanwhile, these systems also provide immediate feedback to subjects regarding identification performance.

5.2.1.2. Safety training and education. Computer-based training and education are becoming more popular in construction phase as is recognized to enhance the cognitive learning of the user. Students or novices are used to learn from an experienced professional through a series of curricula by using chalkboard, handouts, and computer presentations that are many words and few visual elements [45]. They have historically lacked a comprehensive knowledge of onsite construction tasks as well as the dynamics and complexities involved in a typical construction project [46]. Although on-the-job training can be more efficient [34] because of the engagement and hands-on experience, it is time-intensive, expensive, and potentially hazardous depending on actual site situations (i.e. schedule conflicts, access difficulties, weather situations, overriding need for safety and liability) [47]. VR/AR technologies afford new opportunities for effectively training and educating novices or students with higher level of cognition and fewer hazards.

VR/AR related technologies have also evolved from visualization-based training to experience-based training in construction safety field (See Fig.10) [15]. They could be applied as a complement to digital modeling, leading to better communication in vocational construction safety education to enhance the students' safety awareness. The study conducted by Lin et al. [48] shown that VR/AR motivate students' learning interests enhances their safety knowledge and help frost their optimistic attitudes towards using the game scoring to reflect their learning performance. Le et al. [49] proposed an online social VR system framework, which allows students to perform role-playing, dialogic learning, and social interaction for construction safety and health education. In order to achieve more interactions between the

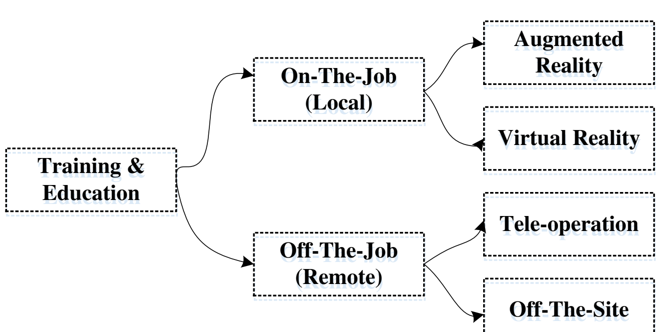

Fig. 10. A Taxonomy of Using VR/AR Systems in Training and Education.

real world and virtual objects, Behzadan and Kamat [50] presented an innovative pedagogical tool that adopting remote videotaping, AR, and ultra-wideband (UWB). The developed system brings live videos of remote construction job sites to the classroom with an intuitive interface for students to interact with the objects in the video scenes. It further visually delivers location-aware instructional materials to students [46].

5.2.1.3. Safety inspection and instruction. Traditional communication methods make inspectors or workers carry construction drawings to the site, and require plenty of efforts to look for the correct drawings to obtain the information they need [39]. They also need to transfer the information from a 2D representation to an imaginary 3D representation, as well as to identify numerous predefined symbols on the drawings [37]. In order to enhance the abilities of recognizing safety risks accurately and promptly, AR has been studied and applied in the construction process of inspection, supervision, and strategizing [51]. AR-assisted building assessment is one kind of inspection application on construction safety. Kamat and El-Tawil [52] discussed the possibility that previously stored building information can be superimposed onto a real structure in AR, and that earthquake-related structural damage can be evaluated by measuring and interpreting critical differences between a baseline image and the actual facility. Dong et al. [37] proposed an AR post-disaster reconnaissance framework that enables building inspectors to rapidly evaluate and quantify structural damage sustained in seismic events such as earthquakes or blasts. As for infrastructure maintenance, AR visual excavator-utility collision avoidance system was developed to enables workers to display buried utilities hidden underground, thus helping prevent accidental utility strikes [53].

Some researchers focused on improving interfaces to provide well-interpreted information for inspectors. The effort has been made on embedding VR or AR for better information representation for safety instructions. ihelmet, developed by Yeh et al. [39], allows inspectors to input their current location at the site, and automatically retrieve the related safety information by AR display. With the applications of AR configured Building Information Modeling (BIM), the exact information context can be disseminated, and safety information can be visualized not only through images or 3D models, but also that of the indoor thermal environment for preventing an uncomfortable working environment [20,54,55]. Workers are able to catch and monitor the difference between unsafe site condition and the standard safety requirements. Taking the function of real-time reporting into account, Bae et al. [35] developed a robust system which adopts a vision-based marker-less AR approach using point cloud for efficient accident precautions. For the cases of site fire or construction disaster, time spent on evacuation is a significant determinant of survival. VR based emergency evacuation simulation, as well as a wayfinding method, is also a validated approach for construction safety instructions to shorten evacuation performance [56].

5.2.2. Challenges faced by VR/AR application domains

5.2.2.1. Hazard identification. Current studies on construction hazard recognition by the applications of VR/AR are still encountered some challenges, including ineffective experiment results, capability difference on risks assessment and hazard forecasting: (1) Hawthorne Effect (subjects improve behaviors under observed) [57] and Practice Effect (subjects improve behaviors under training) may have significant adverse impacts on the experiments conducted by traditional VR-CS systems. Hence, a real-time hazard database or dynamic VR environment may avoid these issues [36]. Adding the fourth dimension, time, to create four-dimensional (4D) environments [5], along with representative audio effects, may significantly improve dynamics in simulating construction projects; (2) The subjects may assess risk levels with different weights given to the judgments of accident severity [41]. An adventurist may underestimate specific risks in construction, and a milquetoast may identify more hazards than ordinary workers [58]. Besides, safety culture including legal liability and safety regulations in different countries/regions affects worker's attitudes to construction hazards. Therefore, it is necessary to conduct comparative experiments among the various subjects, regions or countries [59].

The following research questions are suggested based on this discussion:

- Which technologies could be involved in VR/AR to improve its real-time and human-interactive ability in hazard recognition?
- How to conduct a cross-regional experiment to evaluate different safety cultures in using VR/AR systems for the risk identification?

5.2.2.2. Safety training and education. VR training initially was used to rehearse the construction process and learn the safety hazards in a risk-free virtual environment. Thereby, the information emerged in a virtual environment could be understood and translated easily to workers. However, some challenges are still existed, including limited hands-on experience, low learning or memory curving, high cost in high-risk work training: (1) Most of the current VR-CS are still the off-the-job training in the off-the-site location [31]. These off-the-job VR systems provide workers with limited hands-on experience with real working conditions, thus resulting in a quickly forgotten or inefficient performance when they come to the job site [60]. A close-to-reality and multi-scenarios 3D dynamics environment with time sequence, location, responsibility and knowledge database are needed to do the on-the-job training with multi-users, especially the fast and skillful decision-making training [61]; (2) AR-based on-the-job systems are suitable for safety information-intensive training tasks, which could convert safety information directly from paper-based plans to actual work [62]. However, some physical based training work (i.e., electricity installation) may pose potential safety hazards either in short-range or in long-range. The more teleoperated AR training systems could assist workers to finish the physical-based dangerous jobs in a remote place in the future [63].

The following research concerns are likely to be addressed in the future:

- Could the hybrid training methods that combine on-the-job training with off-the-job training be integrated into VR/AR systems to train multiple trainees in the future?
- What kind of educational methods, theories, and tools could be smoothly embedded into VR/AR systems to improve the performance of training and education?

5.2.2.3. Safety inspection and instruction. Challenges for safety inspection and instruction contain low interoperability of VR/AR-CS information and unskillful visual literacy of workers: (1) Lacking standardization of ICT tools for safety instruction is recognized as the barriers for more accurate and real-time safety inspection or instruction [64]. A mismatch between the level of details (LODs) for BIM and AR always exists, which would cause the rich information-based BIM models not to be well-displayed in AR interfaces; (2) the visual literacy skills should also be improved in order to have higher performance while dealing with visualized objects. A preferable guideline can be chosen as Visual Information-Seeking Mantra [65]: overview first, zoom and filter, then details on demand. Therefore, the following research concern is likely to be addressed in the future:

- How to give a clear taxonomy for combining VR/AR with other ICT tools on display and information retrieval of construction safety?

5.3. Classification of safety enhancement mechanisms and major challenges

The comprehensive investigations about the causes of construction accidents were investigated. It found that the major contributors that cause construction accidents include hazardous site environment, unsafe workers' behavior, unsafe working sequence and high-risk equipment operation [51]. Related safety enhancement mechanisms against these contributors through the uses of VR/AR systems are discussed individually.

5.3.1. State-of-the-art studies of VR/AR safety enhancement mechanisms

5.3.1.1. Working environment. The hazardous working environment is a workplace with abnormal hazards violating the prevailing safety standards and considering unsuitable for work. Inadequate security, broken working platforms and other means of accessing the workplace are also included [8,9]. The VR-based safety training and rehearsal program can offer close-to-reality simulations for the hazardous working environment [66,67]. The users can efficiently rehearse tasks, plan, evaluate and validate the construction safety operations or immerse with different kinds of hazards to ultimately promote their abilities for hazards cognition and intervention [6,68]. It also contributes to raising the situational awareness of workers, equipment operators, and decision-makers on a construction project even in a remote location [33]. Teizer et al. [46] adopted remote data sensing and visualization technology to train workers through the tasks of identifying safety issues. The learning performance with the uses of the unsafe virtual environment was enhanced through the ease of recording and visualizing the nearby hazards and assessing the learning effect [67]. A virtual safety assessment system (VASA) was successfully developed and evaluated by trials and post-use interviews [69]. The results indicated that VSAS contributed to pinpoint the weaknesses of construction workers who have passed the traditional assessment process of identifying safety issues in hazardous activities including stone cladding work, ironwork as wells as cast-in-situ concrete work [70].

5.3.1.2. Worker behavior. The lack of proper training is one of the contributory factors to risky worker behavior. Workers who are not well trained tend to be less capable of recognizing hazardous activities, even if well-trained workers may have a negative attitude towards safety. Loss of balance was identified as one of the triggering body behavior in fall-from-height incidents during construction work [71]. Most of the unsafe behavior training studies focus on balance-control training in order to reduce the risk of falls at elevation. Walk training on real construction planks in an immersive VR system, Surround-Screen Virtual Reality (SSVR), was developed by Hsiao et al. [72]. They analyzed the working environment and personal protective equipment (PPE) to provide appropriate training constraints of workers' behavior in the system. For example, shoe design can significantly affect workers' lateral stability during walking on narrow and tilted planks at specific elevation [73]. To reduce the possibility of losing balance, mechanical vibration should be minimized when performing construction tasks at height [74].

5.3.1.3. Working sequence. Insufficiently planned construction tasks can be more hazardous to execute, especially if the work involved is of an unusual nature [75], especially an inappropriate working sequence. This may be due to inadequate method statements, poor design of temporary work, layout plans, schedules or site investigation [76]. The training of construction work sequence typically consists of work and non-workpiece-related activities. The information retrieval effort often increases when using an action sequence manual in complex and intricate processes. It could lead to mental tiredness and proneness to commit errors and safety issues [75]. The insertion of digitalized information into the real workspace using AR can provide workers with intuitive tools to implement correct work procedures, especially assembly procedure with improved accuracy and safety as well as error reduction. Based on the research done by Hou et al. [21], trainees are prone to making mistakes when they relied on their memory and manuals to complete assembly tasks. When the developed AR tool was used, the learning performance of trainees significantly improved, and fewer errors and safety problem were made. Gender also could be an additional factor that can influence the safety post-training performance of novice assemblers [77].

5.3.1.4. High-risk equipment operation. Many accidents are caused by the inappropriate operations of heavy construction equipment such as construction cranes. They are commonly used on construction sites while elegant and safe operations of the equipment are difficult for trainees to achieve given the limited information and sensational control features provided through current training aids. The non-immersive virtual operation is regarded as a low-cost and easy-to-use operating system for equipment training [35]. Li et al. [61] and Guo et al. [78] developed multi-user virtual safety training systems (MVSTS) based on non-immersive game technology, which could simulate the detailed process of dismantling and tower crane operations. They further provide dynamic databases for workers to compare their input with predefined knowledge and rules. Given the development mentioned above, however, the integration of computer simulator with immersive VR environment could give a realistic simulation for depth perceptual feeling. It is expected to reduce experiential differences between virtual simulations and real operations. Juang et al. [79] adopted kinesthetic and stereoscopic (KS) vision into a virtual crane simulator (called SimCrane3D$^+$) to increase training effectiveness and operation confidence. A unique and more intelligent study conducted by Rezazadeh et al. [80] comes out with a virtual crane training system which can be controlled by using control commands extracted from facial gestures to lift uploads or materials in the virtual construction sites for disabled workers. Multi-users and multi-views features were also considered by operation training studies. Kim et al. [38] developed an AR system with collaborative and interactive scenarios for construction equipment operation, which could share the idea with other users in distant locations. A multi-users, multi-views and the collaborative working system was well developed by adopting both VR and AR technology [81]. It provided a more realistic and easy-to-use environment, including better coordination between equipment and materials, a more intuitive control interface, and integrations with structural analysis tools.

5.3.2. Challenges faced by VR/AR safety enhancement mechanisms

There are several challenges in developing appropriate VR/AR safety enhancement mechanisms: (1) some VR/AR systems provide an unsafe collaborative environment that could be used for multi-users to do the same work. However, it could not involve multi-role (i.e., safety manager, workers, operators) into this environment [61] to achieve a complete project-level human-computer interaction interface. (2) There is still a lack of further studies on more diversity unsafe/hazardous behavior training by using VR/AR technologies, such as electric shock and object strike are envisaged to be conducted,which could involve more force sensors to make workers experience the force feedback. (3) Learning and memory curve losses on safety information are substantially reduced during a nonstandard work sequence. However, the real-time work package could give more detail task-based information (according to Work Breakdown Structure (WBS)) to on-site workers [82]. In addition, combing construction work package with VR/AR technologies may provide a seamless and integrated safety guide in an unsafe working sequence. (4) The limitations of generating kinesthetic vision and the dizziness effect caused by the stereoscopic glasses always affect the actual performance in the process of high-risk equipment operation. The following research concerns are likely to be addressed in the future:

- How to design a multi-user environment or collaborative virtual/augmented equipment platform for different trades in one dynamics and complex project?
- Could some work modes (i.e., work package) be involved into VR/AR to make the work sequence more foolproof style and make workers' behavior more skilled?

5.4. Classification of safety evaluation methods and major challenges

5.4.1. State-of-the-art studies of evaluation methods in VR/VR applications

The experiment is the most popular validation method in VR/AR-CS related studies [48,72–74,77,79]. Additionally, the field-based and case study validation process have also been conducted in VR/AR-CS field [35,38,81]. During the implementation process of these validation methods, the subjective (i.e., interviews and questionnaire) and objective (i.e., performance time, the number of errors) evaluation methods are always adopted [83]. From the perspectives of evaluation purposes, the effectiveness, usability, applicability and the level of sense of presence could be regarded as most concerned evaluation effect [15]. Effectiveness was assessed by conducting a comparative experiment with a VR/AR system based group and a traditional process based group, concerning how efficiently a VR/AR system can solve a particular safety issue. Usability and applicability were evaluated by a series of case studies. The former concerns whether the VR/AR system could be used in solving this safety problem, and the latter concerns which subject group (novice or experienced workers) or safety issues could be suitable for VR/AR systems application. For all VR/AR related applications, the level of sense of presence is always important showing the abilities of engaging users and eliminating the sense of deviations between scenarios of VR/AR systems and reality. It can be evaluated in system trials of users through post-training questionnaire survey in terms of users' satisfactions, loading on operations (such as the uses of NASA TLX form) [84], or observations during the trials [85]. A clear taxonomy could be summarized to generalize a hybrid evaluation method for future VR-CS studies as shown in Fig.11 and a detailed application of evaluation methods in construction safety will be discussed in the following.

5.4.1.1. Hazard identification. VR technology acts as an experience-oriented method of safety hazards cognitive for different construction participants in various project/activity/work-task levels. The multiple baseline testing was adopted by Albert et al. [42] which selected six baselines based on occupations (mechanical, civil, maintenance, electrical, structural, and insulation) to conduct the experiment. It is a method for validating the effectiveness of workers in hazard recognition. However, workers in various trades face different types of hazards. Thus, not all the hazards could be presented in this experiment, which results in an inaccurate rate to hazard identification. The empirical records analysis is a subjective evaluation method, which could be useful for a specific project to identify the hazards by designers and builders together [24]. This is a new vision to involve the non-construction related participants (i.e., designers) to evaluate the VR in risk recognition and identification. It could be an efficient way to reduce hidden hazards in the design phase.

5.4.1.2. Training and education. In the process of safety training, most studies utilized the novice and professionals as the comparative subjects through subjective (i.e., interview and questionnaire survey) and objective (i.e., cognitive load, the level of satisfaction, completion time) evaluation methods. As a matter of fact, most of the operatives or workers deemed the safety problems were induced by the personal behavior and attitude [60]. Although these platforms or systems can assist operatives or workers in safety training, it is difficult to avoid the occurrence of safety issues without the workers' commitment [86]. A significant advantage was found for VR training for stone cladding work and for cast-in-situ concrete work, but not for general site safety. VR training was more effective in terms of maintaining trainees' attention and concentration, as well as enhancing the trainees' confidence [6,79]. In addition, trainees performed the walking tasks on real planks in an

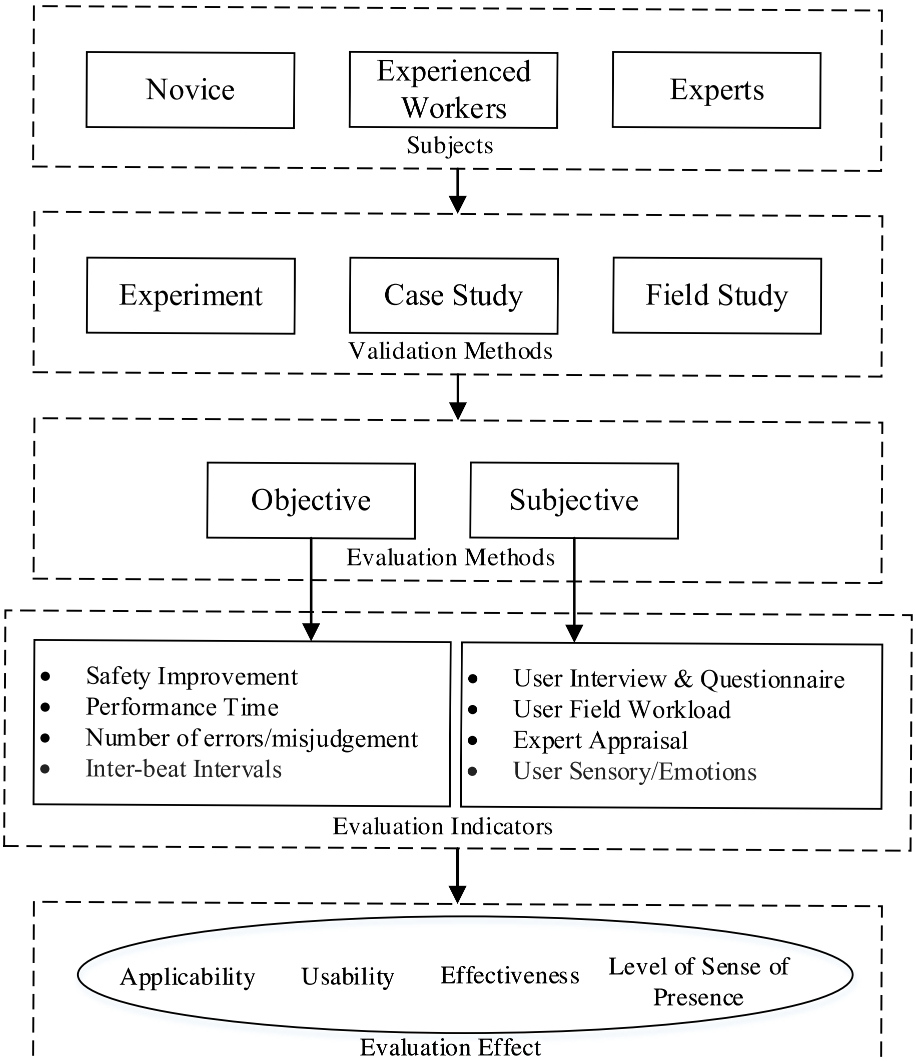

Fig. 11. A Taxonomy for Evaluation Methods Used in VR/AR-CS.

immersed VR scaffolding simulation with more caution, more realistic responses (smaller stride length), less stress, and better stability with than when they were on virtual planks only [72–74].

The standard practice to measure the effectiveness of alternate safety education methods is questionnaire surveys. Notably, students showed optimistic attitudes towards using the game scoring as a way to reflect their safety knowledge [27]. Although questionnaire survey could reveal a subjective measure of students' interest and engagement, this is a secondary metric, and any new technology should be measured by evaluating the degree of knowledge transfer [22]. The incorporation of VR/AR technologies into pedagogical methods or modes should be the development direction for construction safety education. Additional works on easing the practice and studies are associated with VR/AR content generation and reuse. This would allow individual instructors to customize content to fit their particular audience more efficiently, and update information in line with local best practices [27].

5.4.1.3. Inspection and instruction. Validation of safety inspection and instruction include damage inspection [37], information retrieval and safety reporting [35]. Some experiments show that it is feasible to measure drift in damaged buildings as the objective indicators for evaluating the accuracy of AR systems [52]. The effectiveness of retrieving building information was evaluated by comparing the traditional 2D drawings and the AR systems. The results showed that the mean completion times were significantly shorter for participants using the AR systems, and the average success rates of participants arriving at the correct answers were also significantly improved in on-site communication [39]. The potential of the proposed AR based reporting system includes prompt field reporting in 3D information, minimizing the time field personnel spent on accessing project information and communicating with others to resolve an issue/conflict on the job site [35].

5.4.2. Challenges faced by VR/AR safety assessment and evaluation

The following challenges faced by assessment and evaluation process should also be considered in the future studies: (1) Human perception and cognition have their own characteristics and features, and the consideration of this issue by developers during hardware and interface design is vital. So the evaluation methods should be established basing on the performance of mass human experiments. (2) In addition, the user's ability to recognize and understand the data/models in VR environments is a central issue for evaluating. Tasks such as browsing and searching require a specific cognitive activity. So it is necessary to give training on the ability and knowledge of system functions to workers before start the evaluation process. (3) Also, there can be issues related to different users' reactions with regard to visualized objects depending on their personal and cultural backgrounds. In this sense, simplicity in information visualization in the evaluation process has to be achieved in order to avoid misperceptions and cognitive overload. (4) Psychophysical studies and theories would provide answers and methods to questions regarding perception and would give the opportunity to improve performance evaluation by motion prediction in construction safety application.

The following research questions are proposed in this section:

- How to make a detailed comparison and benchmarking of experienced vs. inexperienced crews, individuals, trainers, operators, training centers, companies in VR/AR-CS?
- How to make the evaluation process/method (i.e., reward systems for safe performance during training sessions) more automatic?
- How to evaluate VR/AR systems in the aspects of sensor type, signal noise, receiver layout?

6. Conclusion

VR/AR-CS has received a considerable amount of attention within the research and construction industry in the past two decades. This study has provided a critical review of the development of VR/AR-CS in the academic field, and hence, has established a solid platform for scholars and professionals to obtain useful insights into VR/AR-CS concerns. Research into VR/AR-CS has been conducted from different perspectives including (1) technology characteristics; (2) application domains; (3) safety enhancement mechanisms; and (4) safety assessment and evaluation. It was also found that numerous VR/AR systems had been proved as efficient, usable, applicable and accurate approaches in hazards identification, safety training and education, safety inspection and introduction (See Table 2). Hazardous construction scenarios have also been simulated interactively, and VR/AR safety enhancement mechanisms have been proposed in the aspects of the working environment, workers' behavior, high-risk equipment, and working sequence. The analysis of these contributions to VR/AR-CS research may also facilitate scholars and professionals to seek further collaborative research opportunities.

Identification of research trends in VR/AR-CS allows industry professionals to appreciate the critical concerns in VR/AR-CS development and to better prevent and control the construction safety issues by advanced technologies [87]. This study is an attempt to synthesize the current body of knowledge related to the applications of VR/AR environments in the construction safety. In the future, research on VR/AR-CS will cover numerous disciplines including construction engineering, ICT tools, safety science, ergonomics, and psychology. Such multidisciplinary research is also an essential driver for VR/AR-CS innovations. Given these and the summary of challenges in Table 2, five trends of future development are anticipated: (1) the increasing rate of complex construction engineering could result in more intractable safety issues, the ICT tools with VR/AR support are the vital tools to be developed for achieving practical functions in improving safety performance; (2) the body of knowledge on safety science will contribute to more clear principles to support the VR/AR methods or tools for solving construction safety issues; (3) the approaches on ergonomics considering numerous human factors could become one of the critical assessment on VR/AR-CS systems; (4) the applicable theories in psychology will be adopted to make more situational experiments for evaluating the application effect of VR/AR-CS systems; and (5) the finer details of VR/AR environment are expected to attract significant attention on establishing more safety incidents' simulations to specifically examine and discuss the immediate reaction and response of workers. These development trends could make an optimal combination to improve the future safety management in construction industry.

Although much effort has been made to review the significant developments in VR/AR-CS research, it is acknowledged that this review is not exhaustive and only limited to the construction industry. Future research effort should be directed towards VR/AR-based safety management in other sectors. A benchmark or baseline for various functions and experimental evaluation methods of VR/AR safety systems in different projects or work tasks has not been thoroughly discussed. Therefore, more research effort should be put in this direction. This is no doubt as well that the overall improvement of VR/AR-CS cannot be achieved without the integrated and concerted effort of all laboratory-based and project-based applications at the technical, experimental, and organizational levels.

Acknowledgement

The authors are grateful to Dr. Lei Hou for his guidance, comments,and suggestions on this research. This research was undertaken with the benefit of a grant from Ministry of Science and Technology of the People's Republic of China, The Thirteenth Five-Year National Key

Table 2
Brief summary of achievement and challenge in VR/AR-CS.

VR/AR-CS	Achievement	Challenge
Technology characteristics	*Virtual reality:* from least to full immersive VR *Augmented reality:* from tangible and collaborative AR to distributed AR	Lack of Information Requirements for VR/AR-CS; Lack of Customized hardware and software for VR/AR-CS; Poor connectivity and interoperability between VR/AR systems and other ICT tools
Application domains	*Hazard identification:* modeling and visualization of collaborative VR environments for hazard identification with performance assessment systems	Lack of detailed investigation on the immediate reaction and response of workers when safety incidents happen and lack of evaluation on different safety cultures in using VR/AR systems for the risk identification
	Safety training and education: experience-based training with higher level of cognition and fewer hazards by Off-the-job VR and on-the-job AR	The needs for the hybrid training pedagogy that combines on-the-job training with off-the-job training.
	Safety inspection and instruction: integrating other ICT tools with VR/AR to provide well-interpreted information to catch and monitor the difference between unsafe site condition and the standard safety requirements	The needs of a standard for combining VR/AR with other ICT tools on display and information retrieval of construction safety
Safety enhancement mechanisms	*Working environment:* a multi-users, multi-views and the collaborative working environment	Lack of multi-role for achieving a complete project-level human-computer interaction environment
	Worker behavior: balance-control training	The needs of diversity unsafe/hazardous behavior training
	Working sequence: intuitive tools to implement correct work procedures	Lack of a real-time safety work package to give more detail task-based safety information
	High-risk equipment operation: integration of computer simulator with immersive VR environment to reduce experiential differences between virtual simulations and real operations	The limitations of generating kinesthetic vision and the dizziness effect caused by the stereoscopic glasses always affect the actual performance in the process of high-risk equipment operation.
Safety assessment and evaluation	*Subjective method:* user interviewer and questionnaire, user field workload, expert appraisal, user sensory and emotions	The needs of conducting mass human experiments covering different personal and cultural backgrounds for obtaining the accurate human perception and cognition
	Objective method: safety improvement, performance time, number of errors and misjudgment, inter-beat intervals	The needs of automatic evaluation process and method

Research & Development Projects (Project No. 2016YFC0702005-04, 2016YFC0701600).

References

[1] A. Rostami, J. Sommerville, I.L. Wong, C. Lee, Risk management implementation in small and medium enterprises in the UK construction industry, Eng. Constr. Archit. Manag. 22 (1) (2015) 91–107, http://dx.doi.org/10.1108/ECAM-04-2014-0057.

[2] Z. Zhou, Y.M. Goh, Q. Li, Overview and analysis of safety management studies in the construction industry, Saf. Sci. 72 (2015) 337–350, http://dx.doi.org/10.1016/j.ssci.2014.10.006.

[3] Y. Zhou, L.Y. Ding, L.J. Chen, Application of 4D visualization technology for safety management in metro construction, Autom. Constr. 34 (2013) 25–36, http://dx.doi.org/10.1016/j.autcon.2012.10.011.

[4] C.-S. Park, H.-J. Kim, A framework for construction safety management and visualization system, Autom. Constr. 33 (2013) 95–103, http://dx.doi.org/10.1016/j.autcon.2012.09.012.

[5] M. Golparvar-Fard, F. Peña-Mora, S. Savarese, Integrated sequential as-built and as-planned representation with D 4 AR tools in support of decision-making tasks in the AEC/FM industry, J. Constr. Eng. Manag. 137 (12) (2011) 1099–1116, http://dx.doi.org/10.1061/(ASCE)CO.1943-7862.0000371.

[6] R. Sacks, A. Perlman, R. Barak, Construction safety training using immersive virtual reality, Constr. Manag. Econ. 31 (9) (2013) 1005–1017, http://dx.doi.org/10.1080/01446193.2013.828844.

[7] H.-L. Chi, S.-C. Kang, X. Wang, Research trends and opportunities of augmented reality applications in architecture, engineering, and construction, Autom. Constr. 33 (2013) 116–122, http://dx.doi.org/10.1016/j.autcon.2012.12.017.

[8] H. Guo, H. Li, V. Li, VP-based safety management in large-scale construction projects: A conceptual framework, Autom. Constr. 34 (2013) 16–24, http://dx.doi.org/10.1016/j.autcon.2012.10.013.

[9] H. Li, G. Chan, M. Skitmore, Visualizing safety assessment by integrating the use of game technology, Autom. Constr. 22 (2012) 498–505, http://dx.doi.org/10.1016/j.autcon.2011.11.009.

[10] X. Li, P. Wu, G.Q. Shen, X. Wang, Y. Teng, Mapping the knowledge domains of Building Information Modeling (BIM): A bibliometric approach, Autom. Constr. 84 (2017) 195–206, http://dx.doi.org/10.1016/j.autcon.2017.09.011.

[11] B. Mullan, L. Smith, K. Sainsbury, V. Allom, H. Paterson, A.L. Lopez, Active behavior change safety interventions in the construction industry: A systematic review, Saf. Sci. 79 (2015) 139–148, http://dx.doi.org/10.1016/j.ssci.2015.06.004.

[12] N.V. Schwatka, S. Hecker, L.M. Goldenhar, Defining and measuring safety climate: a review of the construction industry literature, Ann. Occup. Hyg. 60 (5) (2016) 537–550, http://dx.doi.org/10.1093/annhyg/mew020.

[13] S. Bhoir, B. Esmaeili, State-of-the-Art Review of Virtual Reality Environment Applications in Construction Safety, AEI, 2015, pp. 457–468, , http://dx.doi.org/10.1061/9780784479070.040.

[14] H. Guo, Y. Yu, M. Skitmore, Visualization technology-based construction safety management: A review, Autom. Constr. 73 (2017) 135–144, http://dx.doi.org/10.1016/j.autcon.2016.10.004.

[15] M.J. Kim, X. Wang, P. Love, H. Li, S.-C. Kang, Virtual reality for the built environment: a critical review of recent advances, J. Inf. Technol. Constr. 18 (2) (2013) 279–305 http://www.itcon.org/2013/14.

[16] J. Whyte, Virtual Reality and the Built Environment, Routledge, 2002 (ISBN: 0750653728, 9780750653725).

[17] I.E. Sutherland, The ultimate display, Multimedia: From Wagner to virtual reality, (1965).

[18] J. Lanier, Virtual Reality: The Promise of the Future, Interact. Learn. Int. 8 (4) (1992) 275–279, http://dx.doi.org/10.1061/(ASCE)0887-3801(2009)23:6(384).

[19] S. Benford, C. Greenhalgh, G. Reynard, C. Brown, B. Koleva, Understanding and constructing shared spaces with mixed-reality boundaries, ACM Trans. Comput. Hum. Interact. (TOCHI) 5 (3) (1998) 185–223, http://dx.doi.org/10.1145/292834.292836.

[20] X. Wang, M. Truijens, L. Hou, Y. Wang, Y. Zhou, Integrating Augmented Reality with Building Information Modeling: Onsite construction process controlling for liquefied natural gas industry, Autom. Constr. 40 (2014) 96–105, http://dx.doi.org/10.1016/j.autcon.2013.12.003.

[21] L. Hou, X. Wang, L. Bernold, P.E. Love, Using animated augmented reality to cognitively guide assembly, J. Comput. Civ. Eng. 27 (5) (2013) 439–451, http://dx.doi.org/10.1061/(ASCE)CP.1943-5487.0000184.

[22] A.Z. Sampaio, M.M. Ferreira, D.P. Rosário, O.P. Martins, 3D and VR models in Civil Engineering education: Construction, rehabilitation and maintenance, Autom. Constr. 19 (7) (2010) 819–828, http://dx.doi.org/10.1016/j.autcon.2010.05.006.

[23] S. Bahn, Workplace hazard identification and management: The case of an underground mining operation, Saf. Sci. 57 (2013) 129–137, http://dx.doi.org/10.1016/j.ssci.2013.01.010.

[24] W. Zhou, J. Whyte, R. Sacks, Construction safety and digital design: A review, Autom. Constr. 22 (2012) 102–111, http://dx.doi.org/10.1016/j.autcon.2011.07.005.

[25] F. Remondino, S. Campana (Eds.), 3D Recording and Modelling in Archaeology and Cultural Heritage: Theory and best practices, Archaeopress, Oxford, UK, 2014, p. 171 (ISBN: 1407312308;9781407312309).

[26] W.D. Cannon, W.E. Garrett Jr., R.E. Hunter, H.J. Sweeney, D.G. Eckhoff, G.T. Nicandri, ... J.A. Hill, Improving residency training in arthroscopic knee surgery with use of a virtual-reality simulator: a randomized blinded study, JBJS 96 (21) (2014) 1798–1806, http://dx.doi.org/10.2106/JBJS.N.00058.

[27] J.K. Dickinson, P. Woodard, R. Canas, S. Ahamed, D. Lockston, Game-based trench safety education: development and lessons learned, J. Inf. Technol. Constr. (ITcon) 16 (8) (2011) 119–134 http://www.itcon.org/2011/8.

[28] W. Yi, A.P. Chan, Critical review of labor productivity research in construction journals, J. Manag. Eng. 30 (2) (2013) 214–225, http://dx.doi.org/10.1061/(ASCE)ME.1943-5479.0000194.

[29] X. Liang, G.Q. Shen, S. Bu, Multiagent Systems in Construction: A Ten-Year Review, J. Comput. Civ. Eng. 30 (6) (2016) 04016016, , http://dx.doi.org/10.1061/(ASCE)CP.1943-5487.0000574.

[30] K.Y. Mok, G.Q. Shen, J. Yang, Stakeholder management studies in mega construction projects: A review and future directions, Int. J. Proj. Manag. 33 (2) (2015) 446–457, http://dx.doi.org/10.1016/j.ijproman.2014.08.007.

[31] F. Bosché, M. Abdel-Wahab, L. Carozza, Towards a mixed reality system for construction trade training, J. Comput. Civ. Eng. 30 (2) (2015) 04015016, , http://dx.doi.org/10.1061/(ASCE)CP.1943-5487.0000479.

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

[33] T. Cheng, J. Teizer, Real-time resource location data collection and visualization technology for construction safety and activity monitoring applications, Autom. Constr. 34 (2013) 3–15, http://dx.doi.org/10.1016/j.autcon.2012.10.017.

[34] A. Pedro, Q.T. Le, C.S. Park, Framework for Integrating Safety into Construction Methods Education through Interactive Virtual Reality, J. Prof. Issues Eng. Educ. Pract. 142 (2) (2015) 04015011, , http://dx.doi.org/10.1061/(ASCE)EI.1943-5541.0000261.

[35] H. Bae, M. Golparvar-Fard, J. White, Image-based localization and content authoring in structure-from-motion point cloud models for real-time field reporting applications, J. Comput. Civ. Eng. 29 (4) (2014) B4014008, , http://dx.doi.org/10.1061/(ASCE)CP.1943-5487.0000392.

[36] A. Perlman, R. Sacks, R. Barak, Hazard recognition and risk perception in construction, Saf. Sci. 64 (2014) 22–31, http://dx.doi.org/10.1016/j.ssci.2013.11.019.

[37] S. Dong, C. Feng, V.R. Kamat, Sensitivity analysis of augmented reality-assisted building damage reconnaissance using virtual prototyping, Autom. Constr. 33 (2013) 24–36, http://dx.doi.org/10.1016/j.autcon.2012.09.005.

[38] B. Kim, C. Kim, H. Kim, Interactive modeler for construction equipment operation using augmented reality, J. Comput. Civ. Eng. 26 (3) (2011) 331–341, http://dx.doi.org/10.1061/(ASCE)CP.1943-5487.0000137.

[39] K.C. Yeh, M.H. Tsai, S.C. Kang, On-site building information retrieval by using projection-based augmented reality, J. Comput. Civ. Eng. 26 (3) (2012) 342–355, http://dx.doi.org/10.1061/(ASCE)CP.1943-5487.0000156.

[40] Y.-S. Jeon, C.-S. Park, A study on the framework of the continuous improvement model of construction process using construction failure information, Korean Journal of Construction Engineering and Management 6 (1) (2005) 195–204.

[41] R. Sacks, J. Whyte, D. Swissa, G. Raviv, W. Zhou, A. Shapira, Safety by design: dialogues between designers and builders using virtual reality, Constr. Manag. Econ. 33 (1) (2015) 55–72, http://dx.doi.org/10.1080/01446193.2015.1029504.

[42] A. Albert, M.R. Hallowell, B. Kleiner, A. Chen, M. Golparvar-Fard, Enhancing construction hazard recognition with high-fidelity augmented virtuality, J. Constr. Eng. Manag. 140 (7) (2014) 04014024, , http://dx.doi.org/10.1061/(ASCE)CO.1943-7862.0000860.

[43] B. Hadikusumo, S. Rowlinson, Integration of virtually real construction model and design-for-safety-process database, Autom. Constr. 11 (5) (2002) 501–509, http://dx.doi.org/10.1016/S0926-5805(01)00061-9.

[44] R. Sacks, O. Rozenfeld, Y. Rosenfeld, Spatial and temporal exposure to safety hazards in construction, J. Constr. Eng. Manag. 135 (8) (2009) 726–736, http://dx.doi.org/10.1061/(ASCE)0733-9364(2009)135:8(726).

[45] L. Ge, F. Kuester, Integrative Simulation Environment for Conceptual Structural Analysis, J. Comput. Civ. Eng. 29 (4) (2014) B4014004, , http://dx.doi.org/10.1061/(ASCE)CP.1943-5487.0000405.

[46] J. Teizer, T. Cheng, Y. Fang, Location tracking and data visualization technology to advance construction ironworkers' education and training in safety and productivity, Autom. Constr. 35 (2013) 53–68, http://dx.doi.org/10.1016/j.autcon.2013.03.004.

[47] X. Wang, P.S. Dunston, A user-centered taxonomy for specifying mixed reality systems for aec industry, J. Inf. Technol. Constr. (ITcon) 16 (29) (2011) 493–508 http://www.itcon.org/2011/29.

[48] K.-Y. Lin, J.W. Son, E.M. Rojas, A pilot study of a 3D game environment for construction safety education, J. Inf. Technol. Constr. 16 (2011) 69–83 http://www.itcon.org/2011/5.

[49] Q.T. Le, A. Pedro, C.S. Park, A Social Virtual Reality Based Construction Safety Education System for Experiential Learning, J. Intell. Robot. Syst. (2014) 1–20, http://dx.doi.org/10.1007/s10846-014-0112-z.

[50] A.H. Behzadan, V.R. Kamat, Enabling discovery-based learning in construction using telepresent augmented reality, Autom. Constr. 33 (2013) 3–10, http://dx.doi.org/10.1016/j.autcon.2012.09.003.

[51] P.S. Dunston, Identification of application areas for Augmented Reality in industrial construction based on technology suitability, Autom. Constr. 17 (7) (2008) 882–894, http://dx.doi.org/10.1016/j.autcon.2008.02.012.

[52] V.R. Kamat, S. El-Tawil, Evaluation of augmented reality for rapid assessment of earthquake-induced building damage, J. Comput. Civ. Eng. 21 (5) (2007) 303–310, http://dx.doi.org/10.1061/(ASCE)0887-3801(2007)21:5(303).

[53] A.H. Behzadan, S. Dong, V.R. Kamat, Augmented reality visualization: A review of civil infrastructure system applications, Adv. Eng. Inform. 29 (2) (2015) 252–267, http://dx.doi.org/10.1016/j.aei.2015.03.005.

[54] R. Lakaemper, A.M. Malkawi, Integrating robot mapping and augmented building simulation, J. Comput. Civ. Eng. 23 (6) (2009) 384–390, http://dx.doi.org/10.

1061/(ASCE)0887-3801(2009)23:6(384).
[55] X. Wang, P.E. Love, M.J. Kim, C.-S. Park, C.-P. Sing, L. Hou, A conceptual framework for integrating building information modeling with augmented reality, Autom. Constr. 34 (2013) 37–44, http://dx.doi.org/10.1016/j.autcon.2012.10.012.
[56] C.-H. Tang, W.-T. Wu, C.-Y. Lin, Using virtual reality to determine how emergency signs facilitate way-finding, Appl. Ergon. 40 (4) (2009) 722–730, http://dx.doi.org/10.1016/j.apergo.2008.06.009.
[57] R. McCarney, J. Warner, S. Iliffe, R. van Haselen, M. Griffin, P. Fisher, The Hawthorne Effect: a randomised, controlled trial, BMC Med. Res. Methodol. 7 (1) (2007) 30, http://dx.doi.org/10.1186/1471-2288-7-30.
[58] X. Luo, H. Li, T. Huang, T. Rose, A field experiment of workers' responses to proximity warnings of static safety hazards on construction sites, Saf. Sci. 84 (2016) 216–224, http://dx.doi.org/10.1016/j.ssci.2015.12.026.
[59] J.K.W. Wong, H. Li, G. Chan, H. Wang, T. Huang, E. Luo, V. Li, Virtual prototyping for construction site Co2 emissions and hazard detection, Int. J. Adv. Robot. Syst. 11 (8) (2014) 130, http://dx.doi.org/10.5772/58439.
[60] J. Lucas, W. Thabet, Implementation and evaluation of a VR task-based training tool for conveyor belt safety training, J. Inf. Technol. Constr. 13 (40) (2008) 637–659 http://www.itcon.org/2008/40.
[61] H. Li, G. Chan, M. Skitmore, Multiuser virtual safety training system for tower crane dismantlement, J. Comput. Civ. Eng. 26 (5) (2012) 638–647, http://dx.doi.org/10.1061/(ASCE)CP.1943-5487.0000170.
[62] X. Wang, P.S. Dunston, Design, strategies, and issues towards an augmented reality-based construction training platform, J. Inf. Technol. Constr. (ITcon) 12 (25) (2007) 363–380 http://www.itcon.org/2007/25.
[63] H.-L. Chi, Y.-C. Chen, S.-C. Kang, S.-H. Hsieh, Development of user interface for teleoperated cranes, Adv. Eng. Inform. 26 (3) (2012) 641–652, http://dx.doi.org/10.1016/j.aei.2012.05.001.
[64] Z. Zhou, J. Irizarry, Q. Li, Applying advanced technology to improve safety management in the construction industry: a literature review, Constr. Manag. Econ. 31 (6) (2013) 606–622, http://dx.doi.org/10.1080/01446193.2013.798423.
[65] B. Craft, P. Cairns, Beyond Guidelines: What Can We Learn from the Visual Information Seeking Mantra? Proceedings of the 9th International Conference on Information Visualisation, Washington, DC, July 6-8, 2005, http://dx.doi.org/10.1109/IV.2005.28.
[66] B. De Vries, S. Verhagen, A. Jessurun, Building management simulation centre, Autom. Constr. 13 (5) (2004) 679–687, http://dx.doi.org/10.1016/j.autcon.2004.03.003.
[67] J. Goulding, W. Nadim, P. Petridis, M. Alshawi, Construction industry offsite production: A virtual reality interactive training environment prototype, Adv. Eng. Inform. 26 (1) (2012) 103–116, http://dx.doi.org/10.1016/j.aei.2011.09.004.
[68] T. Huang, C. Kong, H.L. Guo, A. Baldwin, H. Li, A virtual prototyping system for simulating construction processes, Autom. Constr. 16 (5) (2007) 576–585, http://dx.doi.org/10.1016/j.autcon.2006.09.007.
[69] H. Li, Z. Ma, Q. Shen, S. Kong, The virtual experiment of innovative construction operations, Autom. Constr. 12 (5) (2003) 561–575, http://dx.doi.org/10.1016/S0926-5805(03)00019-0.
[70] D. Zhao, J. Lucas, Virtual reality simulation for construction safety promotion, Int. J. Inj. Control Saf. Promot. 22 (1) (2015) 57–67, http://dx.doi.org/10.1080/17457300.2013.861853.
[71] H. Hsiao, P. Simeonov, Preventing falls from roofs: a critical review, Ergonomics 44 (5) (2001) 537–561, http://dx.doi.org/10.1080/00140130110034480.
[72] H. Hsiao, P. Simeonov, B. Dotson, D. Ammons, T.-Y. Kau, S. Chiou, Human responses to augmented virtual scaffolding models, Ergonomics 48 (10) (2005) 1223–1242, http://dx.doi.org/10.1080/00140130110034480.
[73] P. Simeonov, H. Hsiao, J. Powers, D. Ammons, A. Amendola, T.-Y. Kau, D. Cantis, Footwear effects on walking balance at elevation, Ergonomics 51 (12) (2008) 1885–1905, http://dx.doi.org/10.1080/00140130802562625.
[74] P. Simeonov, H. Hsiao, J. Powers, D. Ammons, T. Kau, A. Amendola, Postural stability effects of random vibration at the feet of construction workers in simulated elevation, Appl. Ergon. 42 (5) (2011) 672–681, http://dx.doi.org/10.1016/j.apergo.2010.10.002.
[75] S. Stork, A. Schubö, Human cognition in manual assembly: Theories and applications, Adv. Eng. Inform. 24 (3) (2010) 320–328, http://dx.doi.org/10.1016/j.aei.2010.05.010.
[76] H. Li, H.L. Guo, M. Skitmore, T. Huang, K.Y.N. Chan, G. Chan, Rethinking prefabricated construction management using the VP-based IKEA model in Hong Kong, Constr. Manag. Econ. 29 (3) (2011) 233–245, http://dx.doi.org/10.1080/01446193.2010.545994.
[77] L. Hou, X. Wang, A study on the benefits of augmented reality in retaining working memory in assembly tasks: A focus on differences in gender, Autom. Constr. 32 (2013) 38–45, http://dx.doi.org/10.1016/j.autcon.2012.12.007.
[78] H. Guo, H. Li, G. Chan, M. Skitmore, Using game technologies to improve the safety of construction plant operations, Accid. Anal. Prev. 48 (2012) 204–213, http://dx.doi.org/10.1016/j.aap.2011.06.002.
[79] J. Juang, W. Hung, S. Kang, SimCrane 3D +: A crane simulator with kinesthetic and stereoscopic vision, Adv. Eng. Inform. 27 (4) (2013) 506–518, http://dx.doi.org/10.1016/j.aei.2013.05.002.
[80] I.M. Rezazadeh, X. Wang, M. Firoozabadi, M.R.H. Golpayegani, Using affective human–machine interface to increase the operation performance in virtual construction crane training system: A novel approach, Autom. Constr. 20 (3) (2011) 289–298, http://dx.doi.org/10.1016/j.autcon.2010.10.005.
[81] A. Hammad, H. Wang, S.P. Mudur, Distributed augmented reality for visualizing collaborative construction tasks, J. Comput. Civ. Eng. 23 (6) (2009) 418–427, http://dx.doi.org/10.1061/(ASCE)0887-3801(2009)23:6(418).
[82] S. Isaac, M. Curreli, Y. Stoliar, Work packaging with BIM, Autom. Constr. 83 (2017) 121–133, http://dx.doi.org/10.1016/j.autcon.2017.08.030.
[83] X. Wang, M.J. Kim, P.E. Love, S.-C. Kang, Augmented Reality in built environment: Classification and implications for future research, Autom. Constr. 32 (2013) 1–13, http://dx.doi.org/10.1016/j.autcon.2012.11.021.
[84] Y.-C. Chen, H.-L. Chi, S.-C. Kang, S.-H. Hsieh, Attention-based user interface design for a tele-operated crane, J. Comput. Civ. Eng. 30 (3) (2016) 04015030, , http://dx.doi.org/10.1061/(ASCE)CP.1943-5487.0000489.
[85] L. Hou, X. Wang, M. Truijens, Using augmented reality to facilitate piping assembly: an experiment-based evaluation, J. Comput. Civ. Eng. 29 (1) (2013) 05014007, , http://dx.doi.org/10.1061/(ASCE)CP.1943-5487.0000344.
[86] S. Lee, Ö. Akin, Augmented reality-based computational fieldwork support for equipment operations and maintenance, Autom. Constr. 20 (4) (2011) 338–352, http://dx.doi.org/10.1016/j.autcon.2010.11.004.
[87] M.J. Skibniewski, Information technology applications in construction safety assurance, J. Civ. Eng. Manag. 20 (6) (2014) 778–794, http://dx.doi.org/10.3846/13923730.2014.987693.
[88] P. Milgram, H. Colquhoun, A taxonomy of real and virtual world display integration, Mixed reality: Merging real and virtual worlds, 1 1999, pp. 1–26.