A Critical Review on Methods for the Assessment of Trainees' Performance in Virtual Reality-based Construction Safety Training

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Abstract. Virtual Reality (VR) is one of the transformative technologies that aid construction safety training. This study is a systematic review of literature on estimating the performance of the trainees during VR-based construction safety training. The critical analysis of the selected literature identified seven focus areas of research, often overlapping with one or more areas. The focus areas include hazard recognition training, personalised feedback, training method improvement, the effect of VR training, the efficacy of VR training, safety behaviour analysis, and automated safety analysis. Most studies focus on either training with existing scenarios for improving hazard recognition or enhancing the training method with the latest technologies or supplementary devices. The possibilities of automated data collection during VR training need to be further explored for quantitatively estimating the participant performance and analysis of close calls or safety incidents.

1. Introduction

Accident rates in the construction industry have been consistently high for decades (Bureau of Labor Statistics, 2020). Conventional classroom-based safety education and training do not adequately prepare the workforce for complex and dynamic construction sites (Wolf et al., 2022). Transformative technological solutions have been explored for improving workplace safety. Virtual Reality (VR) is one of the leading technologies that provides an immersive and interactive learning experience. A VR environment is created through stationary displays such as desktops or CAVE; head-based displays such as head-mounted displays (HMD) or smartphones; or handheld VR devices (Zhang et al., 2020). Earlier studies on construction safety training deployed stationary displays, whereas head-based displays have been widely used now.

The initial studies that featured VR environments mostly implemented it as a visualisation tool (Perlman *et al.*, 2014). The studies on the later stages compared its effectiveness with the existing training methods (Pham et al., 2018). As VR technology advances, the training methods are improved with additional devices (Kim *et al.*, 2021). There are prospects of improving training through dynamic scenario creation with the aid of digital twins (Harichandran *et al.*, 2021). However, most VR-based safety training methods estimated the participants' performance either qualitatively or through manual quantitative estimation (Han *et al.*, 2021). A few studies have explored the possibilities of inbuilt scripting capabilities of game engine software for automated data collection (Golovina *et al.*, 2019). Nevertheless, the existing studies are yet to achieve real-time performance assessment and feedback. Various aspects of VR application in the built environment have been extensively reviewed (Zhang *et al.*, 2020; Rey-Becerra *et al.*, 2021). According to the authors' knowledge, there are no comprehensive reviews that exclusively focus on estimating the performance of the trainees. The objective of this study is to conduct a systematic review of the literature on performance assessment of trainees during VR-based construction safety training. The scope of the review is limited to documents in the Scopus database published from 2011 to 2022.

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2. Research Method

This study has adopted a systematic review method where the data is collected through well-defined criteria to include relevant and high-quality publications. Scopus is a literature database that encompasses various disciplines, including Virtual Reality (VR), construction management, and safety science. It also offers extensive options for a systematic search compared to other databases such as Google Scholar and Web of Science (Zhang et al., 2020). Therefore, Scopus is selected as the database for retrieving relevant publications for this study.

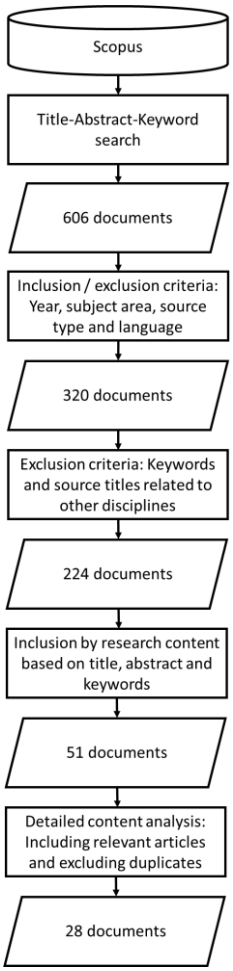

Figure 1: Method for selecting relevant literature.

The method for selecting the literature is illustrated in Figure 1. First, the publications related to VR-based construction safety training that focused on estimating the performance of the trainees were extracted by searching the 'title', 'abstract' and 'keywords of the documents. The code used for the search is: (TITLE-ABS-KEY (("virtual reality") OR ("virtual environment") OR ("serious game")) AND TITLE-ABS-KEY (("construction safety") OR ("safety training") OR ("training environment")) AND TITLE-ABS-KEY (("data collect*") OR ("collect data*") OR ("analy*") OR ("performance") OR ("feedback"))). The Boolean operator 'OR' is applied to look for alternate words or synonyms, while 'AND' is applied to include relevant literature that contains all the critical search elements. The double quotes characters ("") ensure that the words inside are searched together for avoiding irrelevant literature. The asterisk character (*) is suffixed to a term (or some terms) for retrieving results that start with its predecessor. These specifications ensured only literature relevant to the objective of the study was captured in the initial search. The initial search resulted in 606 documents which were then filtered through

various inclusion and exclusion criteria. The first stage of filtering applied criteria related to year of publication, subject area, source type and language. Virtual reality and related technology are continuously evolving. Therefore, the latest ten years of research adequately represent the most relevant literature. The publications from 2011 to 2022 were considered for this study since the search was conducted in early April 2022. The subjects selected include Computer Science, Engineering, Social Sciences, Mathematics, Decision Sciences, and Business, Management and Accounting. The source type is limited to journals and conference proceedings. The language of publications is set as English. The search resulted in 320 documents after applying these criteria.

The authors observed that some of the results are medical publications related to drug safety, medical training, or clinical competence. Therefore, exclusion criteria are applied to remove documents that contain keywords related to medical research. The search after applying these criteria retrieved 224 documents related to VR research in construction safety training. The authors then intensively read the title, abstract and keywords; and scanned the outline of these documents to analyse the research content. The selected documents include 51 publications on VR for construction safety training. Finally, detailed content analysis has been performed by rigorously reviewing these publications. The authors paid attention to selecting the studies focusing on assessing the performance of the trainees in the VR environment. The conference publications later elaborated and published in peer-reviewed journals were considered duplicates and removed. The outcome of the final filtering resulted in 28 documents, and a critical analysis of these publications is presented in this study.

3. Analysis, Results and Discussion

3.1 An Overview of The Literature

The content analysis of the database search results narrowed the outcomes to 51 publications on construction safety training based on VR. The authors are interested in a subset of these studies (28 publications) that estimate the performance of the trainees in the VR environment. An overview of these publications based on the sources are provided in Table 1. The most relevant studies are published in journals such as 'Automation in Construction', 'Advanced Engineering Informatics', 'Journal of Construction Engineering and Management', and 'International Journal of Occupational Safety and Ergonomics'. The journals such as 'Accident Analysis and Prevention', 'IEEE Transactions on Visualization and Computer Graphics', and 'Safety Science' also publish equally relevant content. Early ideas, preliminary results of the ongoing research and proof of concepts are presented in conferences such as International Symposium on Automation and Robotics in Construction (ISARC) and Construction Research Congress (CRC). Notably, the proceedings of these conferences are among the top sources that offer the most number of publications. However, journal articles provide 67 – 68 per cent of the relevant literature on VR research in construction.

The number of studies on VR applications in the built environment is rising (Zhang et al., 2020) and the latest search conducted for this study also shows a similar trend for the past ten years. The current study focuses explicitly on VR applications for construction safety training. The trend of research publications from 2011 is illustrated in Figure 2. The drops at the end of the curves are due to the time at which this study is conducted. More publications can be expected towards the end of this year based on the past data. The VR has been actively explored in several construction domains, such as architectural and engineering design, project management, human behavioural studies, and engineering education. The limited number of publications

observed in this study is due to the specific focus on construction safety training. Studies on other aspects of construction safety, such as inspection and planning, have been omitted. Therefore, some years (2011, 2015, 2017) may have very little or no publications on VR based safety training.

Table 1: Overview of the VR research publications in various sources.

Source of publication	Number of publications in	
	VR for construction safety training	Trainee performance assessment
International Symposium on Automation and Robotics in Construction (ISARC)	9	7
Automation in Construction	7	4
Advanced Engineering Informatics	5	2
Construction Research Congress (CRC)	5	1
Journal of Construction Engineering and Management	4	2
International Journal of Occupational Safety and Ergonomics	3	2
Accident Analysis and Prevention	2	2
IEEE Transactions on Visualization and Computer Graphics	2	2
Safety Science	2	1
Construction Innovation	1	1
Engineering, Construction and Architectural Management	1	1
IEEE International Conference on Architecture, Construction, Environment and Hydraulics (ICACEH)	1	1
International Journal of Engineering Education	1	1
Journal of Engineering Education	1	1
Annual Conference of the International Group for Lean Construction (IGLC)	1	0
Buildings	1	0
Institute of Industrial and Systems Engineers Annual Conference and Expo (IISE)	1	0
Journal of Civil Engineering Education	1	0
Journal of Management in Engineering	1	0
Journal of Safety Research	1	0
Procedia Engineering	1	0
Total number of publications	51	28

The distribution of publications based on the country or region is presented in Figure 3. The USA has the highest number of publications on VR-based construction safety training and studies covering trainee performance assessment. Many publications have emerged from countries such as Germany, China, Denmark, Hong Kong, and India. Most of the collaborative research was conducted within the countries or regions. This may be because VR research is highly dependent on the training facilities and lab space available. However, a few experimental studies show collaborations between countries (Choi *et al.*, 2020; Wolf *et al.*, 2022).

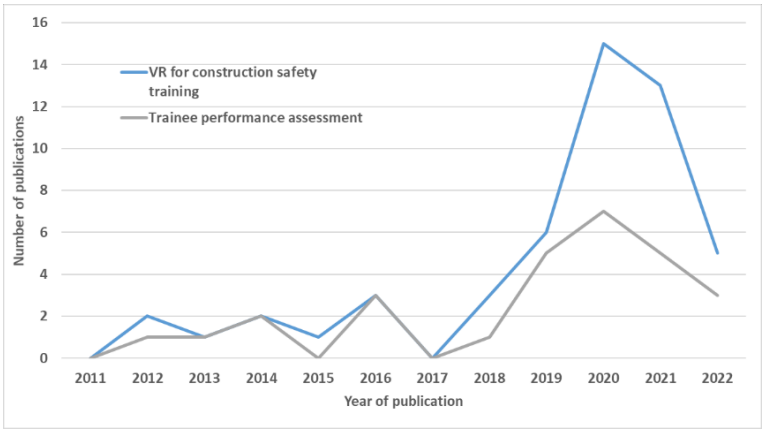

Figure 2: Year-wise research publications on VR based construction safety training and trainee performance assessment.

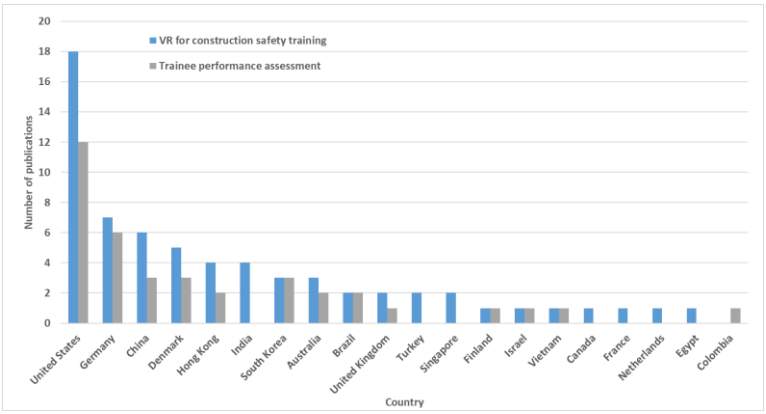

Figure 3: Distribution of VR research publications based on country or region.

3.2 Performance Assessment in Virtual Reality Training

The studies on trainee performance assessment were selected from the VR-based construction safety training publications. A systematic review of the selected research publications was conducted for in-depth analysis of the contents. The results of the content analysis are summarised in Table 2. Seven research focuses were identified: 1) training for hazard recognition (THR), 2) personalised feedback to the trainees for improving the safety performance (PFT), 3) studies that support or improve the VR based safety training (TMI), 4) effect of VR training on trainees (VRT), 5) estimating the efficacy of VR based safety training and/or benchmarking with conventional training methods (EVR), 6) analysing the safety behaviour of the trainees (SBT), 7) automatically analysing the close call events and safety incidents (ASA). The distribution of these research focus areas across the selected studies is presented in Figure 4.

From the initial applications of VR for construction safety training, the studies were focused on training the workers to identify hazards or potential hazards (Gupta and Varghese, 2020). The earlier studies merely visualised hazards and manually recorded the performance in hazard identification (Perlman *et al.*, 2014). Latest training methods involve the automatic player data collection through inbuilt C# scripts and colliders embedded in the VR training environment (Golovina *et al.*, 2019; Moelmen *et al.*, 2021). These data can be further used to provide personalised feedback to the trainees to improve their performance (Wolf et al., 2022). A few studies have focused on personalised feedback in safety training. Similarly, very little focus has

been given to the automated analysis of close call events and safety incidents. The interaction between trainees and surrounding objects can be automatically recorded to generate data that will eventually aid in quantitative safety analysis (Golovina *et al.*, 2016).

Table 2: Summary of the content analysis of literature on trainee performance assessment.

Research paper	Focus of the study						
	THR	**PFT**	**TMI**	**VRT**	**EVR**	**SBT**	**ASA**
(Li et al., 2022)	X						
(Lucena and Saffaro, 2022)	X						
(Wolf et al., 2022)	X	X					
(Habibnezhad et al., 2021)			X				
(Han et al., 2021)				X			
(Kim *et al.*, 2021)					X		
(Jacobsen et al., 2021)	X	X					
(Moelmen et al., 2021)				X			
(Choi *et al.*, 2020)						X	
(Jeelani *et al.*, 2020)	X	X					
(Noghabaei and Han, 2020)	X					X	
(Chihming et al., 2020)	X		X				
(Nykänen *et al.*, 2020)					X		
(Hasanzadeh *et al.*, 2020)				X		X	
(Pedro et al., 2020)			X	X			
(Ye and König, 2019)	X		X				
(Shi et al., 2019)						X	
(Habibnezhad et al., 2019)			X	X			
(Wolf *et al.*, 2019)		X	X				
(Golovina et al., 2019)		X					X
(Pham et al., 2018)					X		
(Pinheiro et al., 2016)	X		X				
(Hilfert *et al.*, 2016)	X		X				
(Golovina *et al.*, 2016)							X
(Perlman *et al.*, 2014)	X				X		
(Albert et al., 2014)	X			X	X		
(Teizer *et al.*, 2013)			X				
(Guo et al., 2012)			X				

Several studies explore the potential of existing VR devices and supplementary devices to enhance the learning experience. Eye-tracking technology for estimating the attention of the trainees (Chihming *et al.*, 2020) and trackers for incorporating the gait movements are some examples (Habibnezhad *et al.*, 2019). Some of the studies focus on the effect of VR training on participants in terms of cognitive load, attention span and knowledge retention. Most of these

studies analyse these effects based on self-assessment questionnaires or manual observation (Albert *et al.*, 2014; Han *et al.*, 2021). A few of the studies have collected run time participant data for quantitative estimation of the effect of VR training (Moelmen *et al.*, 2021). The efficacy of VR training has been estimated through statistical methods such as generalised linear mixed modelling, bivariate linear regression analysis, and multilevel modelling (Nykänen *et al.*, 2020; Kim *et al.*, 2021). Generally, the studies that focus on training efficacy involved a larger number of participants than the studies focused on hazard identification or training method improvement. Another advantage of VR-based training is exposing the trainees to unsafe situations and assessing their behaviour. Situational awareness, risk-taking behaviour or the effect of interventions can be quantitatively estimated through various measures such as time and frequency of gazing, position and heart rate measurements through external devices (Choi *et al.*, 2020; Hasanzadeh *et al.*, 2020). Even though several research directions have been explored in VR based construction safety training, the possibilities of automated data collection and analysis have not been fully explored yet.

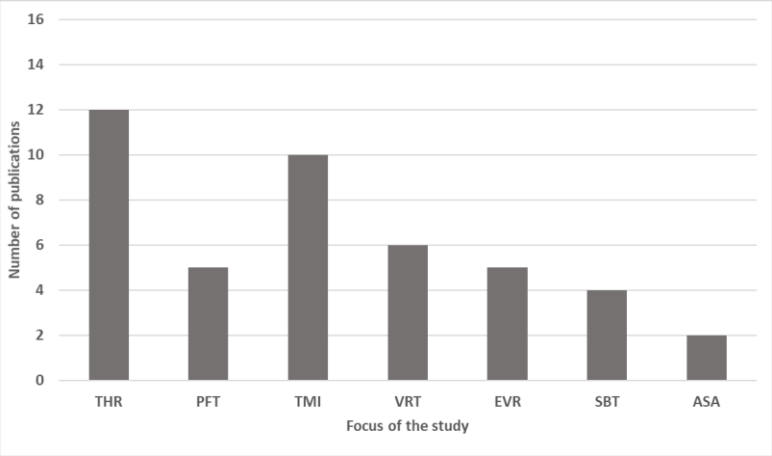

Figure 4: Research focus of studies on trainee performance assessment during VR based construction safety training.

4. Conclusions

Virtual Reality (VR) based safety training provides a more realistic and interactive learning experience than conventional classroom training. The application of VR in construction and built environments has been widely studied and reviewed. However, a study that exclusively focused on estimating the performance of the trainees during VR based construction safety training does not exist according to the authors' knowledge. This study conducts a systematic review of literature relevant to this domain. The content analysis of the Scopus database search resulted in 51 publications on construction safety training based on VR. A subset of these studies consists of 28 publications that estimate the performance of the trainees in the VR environment; they have been selected for in-depth analysis.

The selected studies were distributed into seven focus areas, often overlapping with one or more areas. The focus areas include hazard recognition training, personalised feedback, improving training methods, the effect of VR training, the efficacy of VR training, safety behaviour analysis, and automated safety analysis. Most studies focus on either training with existing scenarios for improving hazard recognition or enhancing the training method with the latest technologies or supplementary devices. The possibilities of automated data collection during VR training need to be further explored for generating a quantitative estimate of the participant

performance and analysis of close calls or safety incidents. Creating dynamic training scenarios from the digital twin of the construction site is another future direction for VR based safety training.

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