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The effectiveness of traditional tools and computer-aided technologies for health and safety training in the construction sector: A systematic review

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ABSTRACT

For workers, the exposure to on-site hazards can result in fatalities and serious injuries. To improve safety outcomes, different approaches have been implemented for health and safety training in the construction sector, such as traditional tools and computer-aided technologies (e.g., serious games, computer-generated simulations, virtual reality, augmented reality, and mixed reality). However, the effectiveness of these approaches has been barely explored. In order to bridge this gap, a systematic review of existing studies was conducted. Unlike previous review studies in this field that focused on uncovering the technology characters and challenges, this study mainly evaluated the effectiveness of training using traditional tools and computer-aided technologies on the well-being of individuals. Measures of the effectiveness included knowledge acquisition, unsafe behaviour alteration, and injury rate reduction. Results indicated that: 1. the effectiveness of traditional tools is sufficiently supported by statistical evidence; and 2. the use of computer-aided technologies has evidence to support its effectiveness, but more solid evidence is required to support this statement. The systematic review also revealed that the overall performance of computer-aided technologies is superior in several technical aspects compared to traditional tools, namely, representing the actual workplace situations, providing text-free interfaces, and having better user engagement.

1. Introduction

The unprecedented scale of building and infrastructure development is driving the demand for intensive use of labour (Chea, Gurumurthy, & Ruwini, 2019). The construction sector is the fifth largest industry in the New Zealand economy, employing 36,000 more workers in 2012 than it did in 2002 (MBIE, 2013). Workplace accidents in this sector are also on the rise, resulting in increased rates of injury and economic loss (Zhao, McCoy, Kleiner, Smith-Jackson, & Liu, 2016). It was estimated that about 15% of all occupational injuries generated in 2015 in New Zealand occurred in the construction sector, causing a substantial economic loss of roughly $108 million (New Zealand dollars) (ACC, 2016).

H&S training has been essential to the success of construction projects (Guo, Yu, & Skitmore, 2017). A H&S training programme

Abbreviations: NZ, New Zealand; H&S, Health and Safety; TT, Traditional Tools; CAT, Computer-Aided Technologies; SG, Serious Games; CGS, Computer-generated Simulations; VR, Virtual Reality; AR, Augmented Reality; MR, Mixed Reality; HMD, Head-mounted Displays; PBD, Projection-based Displays; HPD, Hearing Protection Devices; PPE, Personal Protective Equipment

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helps the personnel to identify hazards and to react appropriately to control hazards (Seppala, 1995). There are a number of ways in which H&S training can be implemented, such as traditional tools (TT) and computer-aided technologies (CAT) (Gao, Gonzalez, & Yiu, 2017). TT includes traditional techniques such as lecture, toolbox talk, handout, audio-visual material (e.g., video demonstration), computer-based instruction, and hands-on training (Blanchard & Simmering, 2014). However, TT has been considered by some researchers as not an ideal solution for the construction workforce (Guo, Li, Chan, & Skitmore, 2012; Li, Chan, & Skitmore, 2012). As noted in Nielsen (2015), the effective transference of H&S knowledge needs to be in accordance with employees' preferences. Construction workers are experiential learners who tend to lose interest in memorising safety regulations, lack continuous engagement with TT approaches, and would prefer more proactive learning styles (Harfield, Panko, Davies, & Kenley, 2007).

The criticisms of TT have led to an intensive search for new methods, such as computer-aided technologies (CAT) (Guo et al., 2012; Sacks, Perlman, & Barak, 2013). Latest innovations in CAT, such as Serious Games (SG), Computer-generated Simulations (CGS), Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR) have now matured, representing interactive and portable solutions to support H&S training in the construction sector (Chi, Kang, & Wang, 2013). In recent years, training with CAT has gained increased attention from many construction companies all over the world (Kivrak & Arslan, 2019). However, many researchers considered that the construction sector is rushing headlong into CAT without adequate evidence of educational effectiveness (Choi, Hwang, & Lee, 2017; Gao et al., 2017; Kizil & Joy, 2001; O'Neal, Jones, Miller, Campbell, & Pierce, 2007; Ray & Teizer, 2012; Sacks et al., 2013). Effectiveness is essential for successful H&S training in construction firms (Ho & Dzeng, 2010). Benitti (2012) highlights that both industry and academia should understand exactly the effectiveness of new technologies and resist getting caught up in what may turn out to be nothing more than a passing fad.

A number of literature reviews have been published over the past decade on CAT-based construction H&S training (Bhoir & Esmaeili, 2015; Gao et al., 2017; Guo et al., 2017; Li, Yi, Chi, Wang, & Chan, 2018; Wang, Wu, Wang, Chi, & Wang, 2018; Zhou, Irizarry, & Li, 2013). However, these previous reviews contain several limitations. First, although previous reviews have summarised the evidence for some aspects of CAT (e.g., application areas, technical advantages), none of them have provided a comprehensive summary of the effectiveness of CAT. Second, previous reviews in this field have not been very comprehensive, focusing on the literature of CAT rather than performing a systematic review of both TT and CAT studies. This is fundamental to understand the effectiveness of new technologies against traditional methods (Kumar, 2012).

The aim of this study is therefore to carry out a systematic review to overcome the weaknesses identified in previous reviews and attain the following objectives:

- To undertake a review of previous studies on the use of TT and CAT for construction H&S training;
- To present a synthesis of the empirical evidence available thus far on the effectiveness of TT and CAT for construction H&S training.

The remainder of this paper is as follows. Section 2 presents background on CAT techniques (i.e. SG, CGS, VR, AR, and MR). Section 3 specifies the stages involved in the systematic review as the research method. Next, we summarise and interpret the results in Section 4. Section 5 discusses our findings. Finally, Section 6 concludes the paper, lists the limitations, and recommends directions for future research work.

2. Background on computer-aided technologies

The background on CAT techniques (i.e. SG, CGS, VR, AR, and MR) is discussed below.

2.1. Serious games

SG is a type of screen-based video game that explicitly involves educational contents and constructs to address real-life issues (Harteveld, 2011). The aim of SG is to make players face challenges that make sense to real-life situations in order to teach specific topical areas or knowledge and provide tangible learning outcomes (Gao et al., 2017). The process of designing a SG requires the modelling of interactive environments and the creation of consistent storylines (Williams-Bell, Kapralos, Hogue, Murphy, & Weckman, 2015). SG can be better understood by using the three-world theory, where a SG is composed of the worlds of meaning, reality, and play (Harteveld, 2011). The *world of meaning* is the most important factor, which considers the topical area and knowledge to be included for end-users (Harteveld, 2011). The *world of reality* relates to the realism that a game environment reaches in comparison to real-life environments (Harteveld, 2011). The *world of play* involves all the strategies employed in the game to sufficiently engage players so that they complete the entire game (Harteveld, 2011).

2.2. Computer-generated simulations

CGS can be defined as a computer technology that utilises meaningful virtual scenes to recreate what people could encounter in the real world and allows learners to experience the recreated events for the purpose of assimilating knowledge and developing skills (Alinier & Platt, 2014). Petroski (2012) points out that there are obviously some common features between SG and CGS: 1. they are all integrated with educational frameworks; 2. they are all dynamic three-dimensional models of real-world situations; 3. they are all interactive and contextual experiential exercises; and 4. they are all screen-based virtual environment that allows leaners to apply knowledge, skills, and strategies.

Although CGS shares some features in common with SG, there are still fundamental differences that keep CGS from meeting the full-fledged definition of SG. One aspect of this difference is that CGS is not necessarily a competitive exercise and does not involve explicit win or lose state as ultimate goals, which is opposite to how SG behaves (Gredler, 2004). Another distinctive feature of SG is the feedback mechanism that gives learners immediate cues as to how well or poorly they are performing, whereas in CGS such feedbacks are usually not provided (Sauvé, Renaud, Kaufman, & Jean-Simon, 2007). For example, leaners can earn rewards as positive feedbacks for their safe behaviours in SG (Gredler, 2004). Such rewards can be implemented in several forms such as health reserves and access abilities (Gao et al., 2017). Health reserves are medicines, kits, or energy supplies in SG that help restore players' lost health (Zhao, Lucas, & Thabet, 2009). Access ability refers to the ability that players are rewarded with to help them enter new or previously inaccessible game chapters (Gredler, 2004; Greuter et al., 2012).

2.3. Virtual reality

VR is another type of computer technology enabled by different types of VR settings, such as head-mounted displays (HMD) and projection-based displays (PBD), in which the realism of its display is close to real life and participants are fully immersed by visual impact to shape illusive feelings of physically existing in the virtual environment presented (Feng, González, Amor, Lovreglio, & Cabrera-Guerrero, 2018a). HMD refers to the portable VR display enabled by dedicated headsets such as Oculus Rift and HTC Vive (Lavalle, 2015). PBD refers to the large-scale VR display supported by a projection system consisting of multiple projectors and projection screens in a room-size environment such as the CAVE system (cave automatic virtual environment) (Perlman, Sacks, & Barak, 2014). In contrast to the screen-based SG and CGS, it is distinctive of VR to provide users with an experience that is indeed very close to what the real world looks like (Lavalle, 2015). Users move their heads towards visual cues that are not in front of them but cover a much wider arc of the vision angle (Winn, 1993).

2.4. Augmented reality and mixed reality

AR and MR are other two often mentioned cutting-edge visualisation technologies (Guo et al., 2017). Unlike VR, in which its display is isolated from the real world and conforms to purely synthetic scenarios, AR and MR are the merging of real and virtual worlds (Haller, 2006). In AR and MR, the real world physical environment is superposed by computer-generated visual contents (e.g., text, image, and model) to supplement learners' perception of the real world through cameras or HMD devices such as Microsoft's HoloLens (Andujar, Mejias, & Marquez, 2011). Quora (2018) pointed out that MR can be considered the advanced form of AR. He further explained that AR overlays virtual contents on the real-world objects while MR not just overlays but anchors virtual contents to the real world and allows users to interact with the virtual contents.

3. Research method: systematic review

To achieve the research objectives, a systematic review was undertaken in March 2018 in accordance with the following procedure proposed by Khan, Kunz, Kleijnen, and Antes (2003): framing questions for the review, identifying relevant publications, summarising the evidence, and interpreting the evidence.

3.1. Framing questions for the review

Research questions should be initially stated in an explicit way before beginning the review work (Khan et al., 2003). Benitti (2012) notes that in order to gain a comprehensive understanding of the effectiveness of an educational intervention, it is necessary to review: 1. what type of technique is used to deliver the intervention? 2. what topics are taught through the intervention? 3. how is the effectiveness of the intervention evaluated? 4. what is the result for the effectiveness of the intervention?

Based on Benitti's (2012) discussion, four research questions were therefore established for this research:

- Question 1: what types of TT and CAT have been used in previous studies to deliver construction H&S training?
- Question 2: what topics have been taught through construction H&S training in previous studies?
- Question 3: how was the effectiveness of TT and CAT evaluated in previous studies?
- Question 4: what are the results for the effectiveness of TT and CAT, as reported in previous studies?

In answering these questions, we try to gain a comprehensive understanding of the effectiveness of both TT and CAT techniques.

3.2. Identifying relevant publications

To identify relevant publications for the review, a literature search was conducted on the following databases: Scopus (www.scopus.com), Web of Science (www.webofknowledge.com), and Science Direct (www.sciencedirect.com). Scopus has nearly 27 million abstracts, 230 million references and 200 million web pages, which is the largest abstract and citation database of scientific literature (Bar-Ilan, 2008). Web of Science is a large database which hosts peer-reviewed research articles in science and engineering published since 1955 (Wuchty, Jones, & Uzzi, 2007). Science Direct is another world's leading database of scientific and medical research, which covers over 12 million publications from 3,500 academic journals and 34,000 books (Reller, 2018). In conducting the literature search we have not limited the search to any language and time span constraints. The keywords used in searching for literature within the scope of this review were:

- (construction) AND (safety training OR H&S training) AND (traditional OR passive OR education OR intervention) for searching TT-related literature;
- (construction) AND (safety training OR H&S training) AND (serious game OR game OR video game) for searching SG-related literature;
- (construction) AND (safety training OR H&S training) AND (simulation) for searching CGS-related literature;
- (construction) AND (safety training OR H&S training) AND (virtual reality) for searching VR-related literature;
- (construction) AND (safety training OR H&S training) AND (augmented reality) for searching AR-related literature;
- (construction) AND (safety training OR H&S training) AND (mixed reality) for searching MR-related literature.

The literature search and publication selection process is shown in Fig. 1. This procedure is discussed in greater detail in the next paragraph.

As can be seen in Fig. 1, the literature search in the various databases yielded 569 records on TT (97 from Scopus, 62 from Web of Science, and 410 from Science Direct), 79 records on SG (14 from Scopus, seven from Web of Science, and 58 from Science Direct), 53 records on CGS (22 from Scopus, 16 from Web of Science, and 15 from Science Direct), 109 records on VR (26 from Scopus, 17 from Web of Science, and 66 from Science Direct), 45 records on AR (eight from Scopus, six from Web of Science, and 31 from Science Direct), and ten records on MR (one from Scopus, two from Web of Science, and seven from Science Direct).

We sorted the identified publications by title and found that there were duplicates among them: 131 duplicates on TT, 15 duplicates on SG, 11 duplicates on CGS, 17 duplicates on VR, ten duplicates on AR, and three duplicates on MR. After the removal of duplicates, the remaining records were filtered in accordance with the following two exclusion criteria suggested by Feng et al. (2018a), p. 1. a record is ineligible if there are no TT, SG, CGS, VR, AR or MR related terms in the title and abstract; 2. a record is ineligible if a prototype of TT, SG, CGS, VR, AR or MR is not proposed in the full text. Examining the titles and abstracts resulted in 132 eligible records on TT, 22 eligible records on SG, 14 eligible records on CGS, 21 eligible records on VR, six eligible records on AR, and four eligible records on MR. The full texts of the remaining records were subsequently examined. As a result, a total of 49 publications were considered eligible and retained for the review, including:

- Fifteen records on TT (Albers et al., 1997; Bena, Berchialla, Coffano, Debernardi, & Icardi, 2009; Darragh, Stallones, Bigelow, & Keefe, 2004; Evanoff et al., 2016; Forst et al., 2013; Gilkey et al., 2003; Hong, Ronis, Lusk, & Kee, 2006; Johnson & Ruppe, 2002; Kerr, Savik, Monsen, & Lusk, 2007; Lingard, 2002; Lusk et al., 1999; Neitzel et al., 2008; Seixas et al., 2011; Sokas, Emile, Nickels, Gao, & Gittleman, 2009; Spangenberg, Mikkelsen, Kines, Dyreborg, & Baarts, 2002);
- Sixteen records on SG (Chen, Golparvar-Fard, & Kleiner, 2013; Dawood, Miller, Patacas, & Kassem, 2014; Dickinson, Woodard, Canas, Ahamed, & Lockston, 2011; Greuter & Tepe, 2013; Guo et al., 2012; Ku & Mahabaleshwarkar, 2011; Le & Park, 2012; Le, Pedro, & Park, 2015b; Leong, Goh & Ieee, 2013; Li et al., 2012; Liaw, Lin, Li, & Chi, 2012; Lin, Son, & Rojas, 2011; Newton, Lowe, Kember, Wang, & Davey, 2013; Pedro, Le, & Park, 2015; Zhao et al., 2009; Zhao & Lucas, 2015);
- Three records on CGS (Fang, Teizer, & Marks, 2014; Li, Lu, Chan, & Skitmore, 2015; Zhao, Thabet, McCoy, & Kleiner, 2012);
- Seven records on VR (Azhar, 2017; Hilfert, Teizer, & König, 2016; Jeelani, Han, & Albert, 2017; Pena & Ragan, 2017; Sacks et al., 2013; Shamsudin, Mahmood, Rahim, Mohamad, & Masrom, 2018; Xie, Tudoreanu, & Shi, 2006);
- Five records on AR (Behzadan, Iqbal, & Kamat, 2011; Le et al., 2015a; Pereira, Gheisari, & Esmaeili, 2018; Wang & Dunston, 2007; Wang, Dunston, & Skiniewski, 2004);
- Three records on MR (Bosché, Abdel-Wahab, & Carozza, 2015; Carozza, Bosché, & Abdel-Wahab, 2015; Segura, Moreno, Brunetti, & Henn, 2007).

4. Results

4.1. Summarising the evidence

In this step, the retained publications were reviewed and the evidence was gathered from the literature to answer the four research questions elaborated in Section 3.1.

Table 1 provides a summary of the evidence retrieved from the retained TT studies. Column 1 gives a complete list of the retained TT studies. Column 2 introduces the types of techniques that have been used in TT studies to deliver construction H&S training (the answer to question 1). Column 3 shows the topics that have been taught through construction H&S training in TT studies (the answer to question 2). Columns 4 and 5 present the relevant evidence on how the effectiveness of TT was evaluated in the retained studies (the answer to question 3). Columns 6, 7 and 8 provide data on the effectiveness of TT, as observed in the retained studies (the answer to question 4). These aspects are introduced here and then interpreted in greater detail in the next section.

Table 2 provides a summary of the evidence retrieved from the retained CAT studies. Column 1 gives a complete list of the retained CAT studies. Column 2 introduces the types of techniques that have been used in CAT studies to deliver construction H&S training (the answer to question 1). Column 3 shows the topics that have been taught through construction H&S training in CAT studies (the answer to question 2). Columns 4 and 5 present the relevant evidence on how the effectiveness of CAT was evaluated in the retained studies (the answer to question 3). Columns 6, 7 and 8 provide data on the effectiveness of CAT, as observed in the

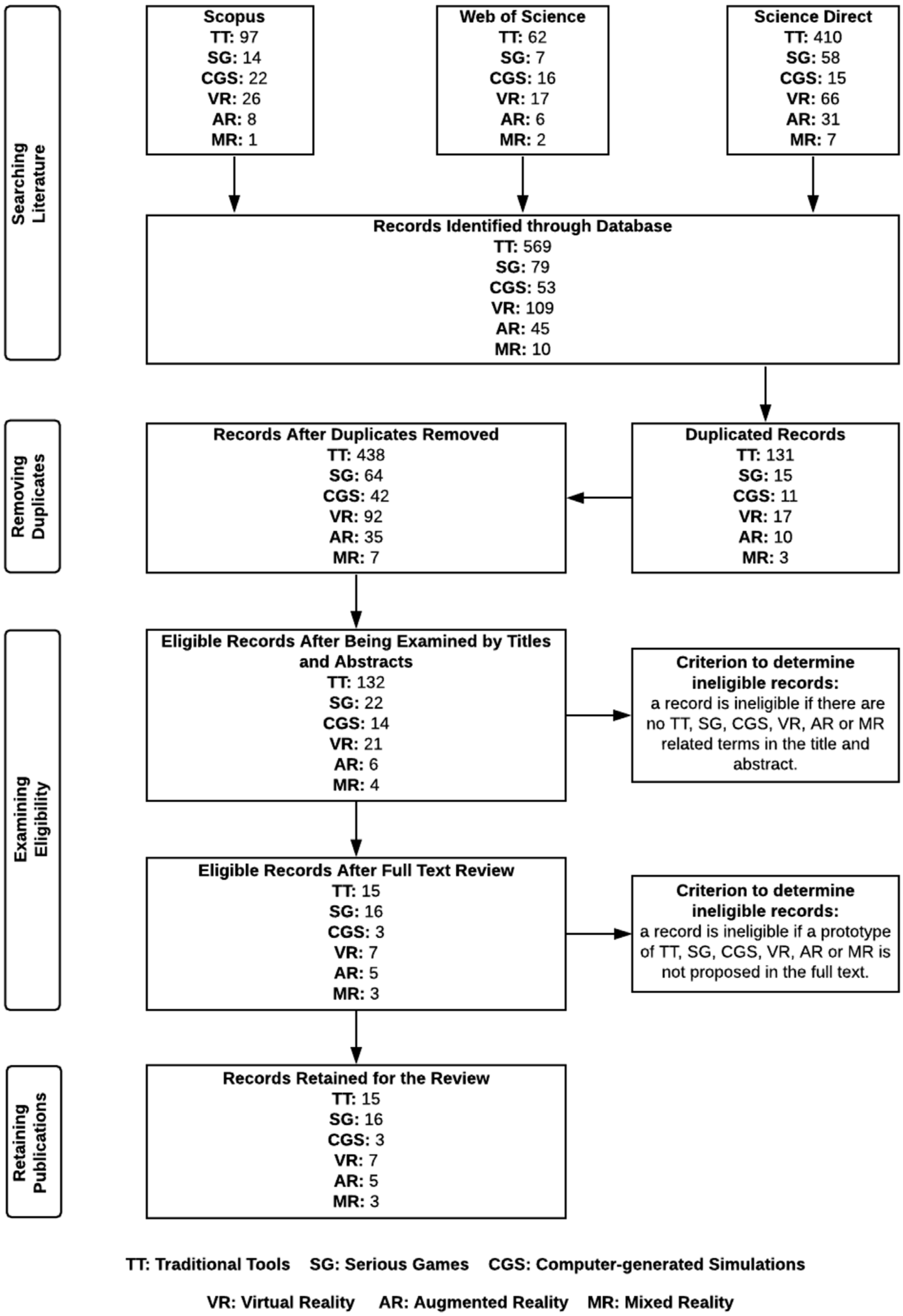

Fig. 1. Literature search and publication selection process.

retained studies (the answer to question 4). These aspects are introduced here and then interpreted in greater detail in the next section.

4.2. Interpreting the evidence

In this section, the evidence retrieved from the retained TT and CAT studies is analysed and interpreted in greater detail, in an attempt to answer the four research questions elaborated in Section 3.1.

Table 1
Training delivery techniques, training topics, samples and sample sizes, data collection methods, factors to assess, retrieved data, and effectiveness of retained TT studies.

Publications	Delivery Techniques	Training Topics	Samples (Sizes)	Data Collection Methods	Factors to Assess	Retrieved Data[a]	Effectiveness[b]
Albers et al. (1997)	Audio-visual Materials, Lecture	Ergonomic Awareness	Worker (37)	Self-report	Knowledge Acquisition	Control Group: 68%, 75%, 51%, 74% Treatment Group: 85%, 80%, 58%, 86%	16% (average)
Lusk et al. (1999)	Handout, Audio-visual Materials	Hearing Protection	Worker (837)	Self-report	Behaviour Alteration	Use of HPD[c]: 46% (Control), 52% (Treatment)	13%
Johnson and Ruppe (2002)	Toolbox Talk	Comprehensive Safety	Worker (50)	Supervisor-report	Injury Rate Reduction	8 injuries in 59,600 h (Pre) 4 injuries in 68,700 h (Post)	56.7%
Lingard (2002)	Lecture, Hands-on Training	First Aid	Worker (25)	Supervisor-report	Behaviour Alteration	Use of power tools: 94% (Pre), 98% (Post) Access to heights: 51% (Pre), 93% (Post) Use of PPE[d]: 65% (Pre), 96% (Post)	44.7% (average)
Spangenberg et al. (2002)	Handout	Comprehensive Safety	Not Mentioned	Supervisor-report	Injury Rate Reduction	25% reduction	25%
Gilkey et al. (2003)	Handout, Toolbox Talk	Comprehensive Safety	Worker (107)	Self-report	Behaviour Alteration	71.8 (Pre), 76.8 (Post)	7%
Darragh et al. (2004)	Lecture	Comprehensive Safety	Not Mentioned	Supervisor-report	Injury Rate Reduction	1,478 injuries in 16,946,918 h (Pre) 493 injuries in 6,706,046 h (Post)	15.5%
Hong et al. (2006)	Audio-visual Materials	Hearing Protection	Worker (612)	Self-report	Behaviour Alteration	Use of HPD[c]: 50% (Pre), 57% (Post)	14%
Kerr et al. (2007)	Computer-based Instruction	Hearing Protection	Worker (343)	Self-report	Behaviour Alteration	Use of HPD[c]: 42% (Pre), 50% (Post)	19%
Neitzel et al. (2008)	Handout, Lecture	Hearing Protection	Worker (23)	Self-report	Behaviour Alteration	Use of HPD[c]: 29.2% (Pre), 57.1% (Post)	95.5%
Bena et al. (2009)	Lecture	Comprehensive Safety	Worker (2795)	Supervisor-report	Injury Rate Reduction	224 injuries in 250,769 days (Pre) 731 injuries in 979,907 days (Post)	16.49%
Sokas et al. (2009)	Lecture, Hands-on Training	Comprehensive Safety	Worker (175)	Self-report	Knowledge Acquisition	Fall Hazard: 2.4 (Pre), 3.1 (Post) Electronic Hazard: 3.7 (Pre), 4.4 (Post)	24% (average)
Seixas et al. (2011)	Handout, Toolbox Talk	Hearing Protection	Worker (176)	Self-report	Behaviour Alteration	Use of HPD[c]: 34.5% (Pre), 46.6% (Post)	35%
Forst et al. (2013)	Lecture	Comprehensive Safety	Worker (446)	Self-report	Knowledge Acquisition	Electrical Shock: 36.9% (Pre), 55.3% (Post) Fall Prevention: 70% (Pre), 72.9% (Post) Electrical Injury: 54.1% (Pre), 58.6% (Post)	20.7% (average)
Evanoff et al. (2016)	Lecture, Hands-on Training	Fall Prevention	Worker (1273)	Supervisor-report	Injury Rate Reduction	18.2 per 100 person-years (Pre) 14.5 per 100 person-years (Post)	20.3%

[a] The data are taken as is from the original papers. The data are briefly presented here and interpreted in greater detail in Section 4.2.4.1.
[b] The results for effectiveness are percent changes estimated by the authors of the present study using the data presented in Column 7: (post - pre)/pre*100%, or (treatment - control)/control*100%.
[c] HPD – Hearing Protection Devices.
[d] PPE – Personal Protective Equipment.

Table 2
Training delivery techniques, training topics, samples and sample sizes, data collection methods, factors to assess, retrieved data, and effectiveness of retained CAT studies.

Publications	Delivery Techniques	Training Topics	Samples (Sizes)	Data Collection Methods	Factors to Assess	Retrieved Data[a]	Effectiveness[b]
Wang et al. (2004)	AR	Machinery Operation	Not Mentioned	Not Mentioned	Not Mentioned	Not Mentioned	Not Mentioned
Xie et al. (2006)	VR	Working at Height	Not Mentioned	Not Mentioned	Not Mentioned	Not Mentioned	Not Mentioned
Segura et al. (2007)	MR	Machinery Operation	Not Mentioned	Not Mentioned	Not Mentioned	Not Mentioned	Not Mentioned
Wang and Dunston (2007)	AR	Machinery Operation	Not Mentioned	Not Mentioned	Not Mentioned	Not Mentioned	Not Mentioned
Zhao et al. (2009)	SG	Working around Electricity	Not Mentioned	Not Mentioned	Not Mentioned	Not Mentioned	Not Mentioned
Behzadan et al. (2011)	AR	Machinery Operation	Not Mentioned	Not Mentioned	Not Mentioned	Not Mentioned	Not Mentioned
Dickinson et al. (2011)	SG	Trench Safety	Student (57)	Self-report	Not Mentioned	Not Mentioned	Not Mentioned
Ku and Mahabaleshwarkar (2011)	SG	Scaffolding Safety	Not Mentioned	Not Mentioned	Not Mentioned	Not Mentioned	Not Mentioned
Lin et al. (2011)	SG	Comprehensive Safety	Student (5)	Self-report	Not Mentioned	Not Mentioned	Not Mentioned
Liaw et al. (2012)	SG	Comprehensive Safety	Student (39)	Self-report	Not Mentioned	Not Mentioned	Not Mentioned
Li et al. (2012)	SG	PPE[c]	Worker (25)	Self-report	Not Mentioned	Not Mentioned	Not Mentioned
Zhao et al. (2012)	CGS	Working around Electricity	Not Mentioned	Not Mentioned	Not Mentioned	Not Mentioned	Not Mentioned
Le and Park (2012)	SG	Scaffolding Safety	Not Mentioned	Not Mentioned	Not Mentioned	Not Mentioned	Not Mentioned
Guo et al. (2012)	SG	Machinery Operation	Worker (15)	Self-report	Not Mentioned	Not Mentioned	Not Mentioned
Chen et al. (2013)	SG	Comprehensive Safety	Worker (36)	Self-report	Not Mentioned	Not Mentioned	Not Mentioned
Greuter and Tepe (2013)	SG	Comprehensive Safety	Student (24)	Self-report	Not Mentioned	Not Mentioned	Not Mentioned
Leong et al. (2013)	SG	Comprehensive Safety	Not Mentioned	Not Mentioned	Not Mentioned	Not Mentioned	Not Mentioned
Newton et al. (2013)	SG	Comprehensive Safety	Not Mentioned	Not Mentioned	Not Mentioned	Not Mentioned	Not Mentioned
Sacks et al. (2013)	VR	Comprehensive Safety	Student (66)	Self-report	Knowledge Acquisition	Score: 11.17 (Control), 13.08 (Treatment)	17%
Dawood et al. (2014)	SG	Comprehensive Safety	Student (12)	Self-report	Not Mentioned	Not Mentioned	Not Mentioned
Fang et al. (2014)	CGS	Machinery Operation	Not Mentioned	Not Mentioned	Not Mentioned	Not Mentioned	Not Mentioned
Bosché et al. (2015)	MR	Working at Height	Not Mentioned	Not Mentioned	Not Mentioned	Not Mentioned	Not Mentioned
Carozza et al. (2015)	MR	Machinery Operation	Not Mentioned	Not Mentioned	Not Mentioned	Not Mentioned	Not Mentioned
Le et al. (2015b)	SG	Working at Height	Student (35)	Self-report	Not Mentioned	Not Mentioned	Not Mentioned
Le et al. (2015a)	AR	Working at Height	Student (40)	Self-report	Not Mentioned	Not Mentioned	Not Mentioned
Li et al. (2015)	CGS	Comprehensive Safety	Worker (10)	Self-report	Not Mentioned	Not Mentioned	Not Mentioned
Pedro et al. (2015)	SG	Comprehensive Safety	Student (25)	Self-report	Not Mentioned	Not Mentioned	Not Mentioned
Zhao and Lucas (2015)	SG	Working around Electricity	Not Mentioned	Not Mentioned	Not Mentioned	Not Mentioned	Not Mentioned
Hilfert et al. (2016)	VR	Machinery Operation	Not Mentioned	Not Mentioned	Not Mentioned	Not Mentioned	Not Mentioned
Azhar (2017)	VR	Comprehensive Safety	Not Mentioned	Not Mentioned	Not Mentioned	Not Mentioned	Not Mentioned
Jeelani et al. (2017)	VR	Comprehensive Safety	Student (4)	Self-report	Not Mentioned	Not Mentioned	Not Mentioned
Pena and Ragan (2017)	VR	Comprehensive Safety	Student (5)	Self-report	Not Mentioned	Not Mentioned	Not Mentioned
Pereira et al. (2018)	AR	Working at Height	Not Mentioned	Not Mentioned	Not Mentioned	Not Mentioned	Not Mentioned
Shamsudin et al. (2018)	VR	Comprehensive Safety	Not Mentioned	Not Mentioned	Not Mentioned	Not Mentioned	Not Mentioned

[a] The data are taken as is from the original papers. The data are briefly presented here and interpreted in greater detail in Section 4.2.4.1.
[b] The results for effectiveness are percent changes estimated by the authors of the present study using the data presented in Column 7: (treatment - control)/control*100%.
[c] PPE – Personal Protective Equipment.

4.2.1. Question 1: what types of traditional tools and computer-aided technologies have been used in previous studies to deliver construction health and safety training?

As can be seen in Column 2 in Table 1, TT training was delivered by means of different techniques such as lecture, toolbox talk, handout, audio-visual material, computer-based instruction, and hands-on training. The results also show that most of the TT studies (8 out of 15) offered the training consisting of a mix of techniques. For example, Sokas et al. (2009) conducted lecture sessions to train workers and provided hands-on opportunities for trainees to practice what they had learned.

In CAT studies, training was delivered through SG, CGS, VR, AR, and MR (Column 2, Table 2). The results show that the majority of the CAT studies (16 out of 34) were based on SG, with three studies on CGS, seven studies on VR, five studies on AR, and three studies on MR.

4.2.2. Question 2: what topics have been taught through construction health and safety training in previous studies?

In TT studies, a wide variety of H&S topics have been taught, including ergonomic awareness, hearing protection, first aid, fall prevention, and comprehensive safety (Column 3, Table 1). Ergonomic awareness programme helps workers develop awareness of the risk of ergonomic hazards in the workplace and attain necessary knowledge on how to protect their backs, necks, shoulders, hands, wrists, elbows, and knees (Albers et al., 1997). Hearing protection programme emphasises the effects of noise on hearing and attempts to increase workers' use of hearing protection devices (HPD) (e.g., Seixas et al., 2011). First aid programme teaches workers how to carry out effective first-aid treatment to casualties in the event of injuries or sudden illness (Lingard, 2002). Fall prevention programme trains workers in fall prevention practices relating to ladder usage, leading edge work, truss setting, and scaffolding usage (Evanoff et al., 2016). Comprehensive safety programme provides trainees with a variety of H&S topics. For example, the training programme by Gilkey et al. (2003) covers a set of 11 H&S topics: safety policy, personal protective equipment (PPE), scaffolding, ladders, electrical power and power cords, fall protection, housekeeping, open holes and unprotected edges, excavations and trenching, power tools, and motorised equipment.

In CAT studies, the following H&S topics have been included: machinery operation, working at height, working around electricity, trench safety, scaffolding safety, PPE, working near machinery, and comprehensive safety (Column 3, Table 2). Machinery operation programme teaches the safe operation of construction machinery (e.g., Carozza et al., 2015). Working at height programme demonstrates the consequences associated with falling from height (e.g., Xie et al., 2006). Working around electricity programme helps learners understand the potential risks associated with electricity in the workplace (e.g., Zhao & Lucas, 2015). Trench safety programme fosters self-protective measures against trench collapse (e.g., Dickinson et al., 2011). Scaffolding safety programme presents dangerous occurrences in relation to the improper use of scaffolding such as insufficient overlaps between planks (e.g., Le & Park, 2012). PPE programme gives lessons on the proper use of PEE such as welding with welding gloves (Li et al., 2012). Comprehensive safety programme covers multiple H&S topics. For example, Lin et al. (2011) provides a comprehensive training platform in which users are instructed to explore the site and spot hazards such as hammer resting on the edge of the scaffold, worker on the ladder reaching too far, and skylight not being covered for roofing construction.

4.2.3. Question 3: how was the effectiveness of traditional tools and computer-aided technologies evaluated in previous studies?

To answer the question of how the effectiveness of an intervention is evaluated, as noted in Benitti (2012), it is necessary to understand two aspects: 1. who is the data for effectiveness collected from (sample and sample size)? 2. how is the data for effectiveness collected (data collection method)? These aspects are introduced here and discussed in more detail in the following subsections.

4.2.3.1. Who is the data for effectiveness collected from (sample and sample size)?. A sample is a representative subset of a targeted population on which data collection is performed (Krejcie & Morgan, 1970). The results show that most of the TT studies (13 out of 15) provided valid information about the samples included in their studies (Column 4, Table 1). As can be seen, all the samples are workers recruited from construction projects. In addition, the sample size varies very significantly among TT studies, ranging from 23 to 2795 workers.

It can also be seen in Column 4 in Table 2, 15 out of 34 CAT studies provided valid information about the samples included in their studies: 11 studies tested their approaches with students, and four studies tested their approaches with workers. The sample size varies greatly among CAT studies, ranging from 4 to 66 students, and from 10 to 36 workers.

4.2.3.2. How is the data for effectiveness collected (data collection method)?. Data from participants can be gathered by means of two methods, namely, self-report, and supervisor-report (Probst, 2004). In the use of self-report, data is reported directly by participants based on their personal experiences (Northrup, 1997). In the use of supervisor-report, data is reported by managers or supervisors based on their observations of participants (Lusk, Baer, & Ronis, 1995).

As can be seen in Column 5 in Table 1, nine TT studies used the self-report method whilst the other six studies adopted the supervisor-report method.

As also can be seen in Column 5 in Table 2, 19 CAT studies did not collect any data (only the detail on SG, CGS, VR, AR, or MR prototypes is provided) while the other 15 studies used the self-report method to collect data.

4.2.4. Question 4: what are the results for the effectiveness of traditional tools and computer-aided technologies, as reported in previous studies?

Effectiveness can be defined as the extent to which a training approach yields desired outcomes (Ho & Dzeng, 2010). Analysing the evidence gathered from the retained studies, we can observe that measures for effectiveness included knowledge acquisition, unsafe behaviour alteration, and injury rate reduction (Column 6, Table 1; Column 6, Table 2).

4.2.4.1. Retrieved data. To understand the effectiveness of TT and CAT training approaches, a group of secondary data were retrieved from the original papers. The data were briefly presented in Column 7 in Tables 1 and 2 and interpreted in greater detail below.

Seven TT studies indicated quantifiable changes in behaviour alteration among participants. Lusk et al. (1999) showed that workers in the treatment group who received training had a higher proportion of HPD use (52%) than the control group not receiving training (46%). Lingard (2002) compared workers' safety behaviours before and after they had received the training, and found that participants exhibited significant improvements in the mean scores on the use of power tools (from 94% to 98%), access to height (from 51% to 93%), and the use of Personal Protective Equipment (PPE) (from 65% to 96%). The training programme by Gilkey et al. (2003) improved the mean score on safety compliance behaviours observed among workers who participated in their study from 71.8 to 76.8. Another four studies reported positive changes in participants' self-reported use of HPD between pre- and post-training: from 50% to 57% (Hong et al., 2006), from 42% to 50% (Kerr et al., 2007), from 29.2% to 57.1% (Neitzel et al., 2008), and from 34.5% to 46.6% (Seixas et al., 2011).

Five TT studies reported evidence on injury rate reduction among participants: 25% reduction (Spangenberg et al., 2002), from 8 injuries in 59,600 h to 4 injuries in 68,700 h (Johnson & Ruppe, 2002), from 1,478 injuries in 16,946,918 h to 493 injuries in 6,706,046 h (Darragh et al., 2004), from 224 injuries in 250,769 days to 731 injuries in 979,907 days (Bena et al., 2009), and from 18.2 per 100 person-years to 14.5 per 100 person-years (Evanoff et al., 2016).

The other three TT studies provided further insights into the acquisition of safety knowledge among participants. Albers et al. (1997) measured participants' knowledge level immediately after training, and found that the treatment group (workers receiving training) outperformed the control group (workers not receiving training), showing the following mean scores: control groups (68%, 75%, 51%, 74%), treatment groups (85%, 80%, 58%, 86%). Sokas et al. (2009) tested workers' safety knowledge immediately after training, and revealed that participants increased their mean scores on fall hazard knowledge from 2.4 to 3.1 and electronic hazard knowledge from 3.7 to 4.4. Forst et al. (2013) evaluated workers' safety knowledge before and immediately after they had received the training, and found that participants exhibited significant gain in mean scores on safety knowledge regarding electrical shock (from 36.9% to 55.3%), fall prevention (from 70% to 72.9%), and electrical injury (from 54.1% to 58.6%).

As mentioned in Section 4.2.3.2, data collection was observed in 44% of the CAT studies (15 out of 34). However, only one CAT study examined the effectiveness in terms of helping participants acquire H&S knowledge (Sacks et al., 2013), while the other 14 studies evaluated their approaches from the usability perspective (e.g., ease of use, clarity of instructions) and data on effectiveness were not available. The study by Sacks et al. (2013) measured participants' knowledge level immediately after training, and showed that the treatment group received VR programme demonstrated greater knowledge acquisition (mean score = 13.08) compared to the control group received traditional classroom programme (mean score = 11.17).

4.2.4.2. Effectiveness. As observed in the retained studies, the data for effectiveness are presented 1) either as the changes in knowledge acquisition, behaviour alteration or injury rate reduction that participants exhibit before and after the implementation of the training programme (i.e. Pre-Post), 2) or as the differences on knowledge acquisition, behaviour alteration or injury rate reduction between control and treatment groups after the implementation of the training programme (i.e. Control-Treatment). However, these data are expressed in different formats (Column 7, Table 1; Column 7, Table 2). To facilitate objective comparison of data with different formats, the data should be converted into a consistent format (e.g., percent change) (Burke, Kingston, & Pepper, 1998; Hadjianastassiou, Karadaglis, & Gavalas, 2001). The results for effectiveness reported in Column 8 in Tables 1 and 2 were therefore percent changes estimated by the authors of the present study using the data presented in Column 7 in Tables 1 and 2: (post - pre)/pre*100%, or (treatment - control)/control*100%.

In general, the results show a learning gain in trainees' knowledge acquisition, behaviour alteration and injury rate reduction with the use of TT techniques (Column 8, Table 1). However, among CAT studies, only the evidence for knowledge acquisition can be observed, and there is a clear lack of evaluation of trainees' behaviour alteration and injury rate reduction (Column 8, Table 2). In addition, previous studies did not provide adequate evidence to prove the effectiveness of all CAT techniques. As mentioned in Section 4.2.1, five different techniques have been used in CAT studies to deliver construction H&S training, namely, SG, CGS, VR, AR, and MR. However, only the evidence for the effectiveness of VR can be observed in the existing literature (Column 8, Table 2), and data on SG, CGS, AR, and MR are not available at this point. Therefore, we cannot confidently argue that the use of CAT is more effective than TT given the limited evidence provided. Nevertheless, the improvements in trainees' knowledge acquisition by using CAT cannot be neglected as evidenced in Table 2.

5. Discussion

The use of CAT for H&S training had evidence supporting its effectiveness, but more solid evidence is yet required to support this statement. Therefore, it is reasonable to ask why many scholars were convinced of the power of CAT (e.g., Dickinson et al., 2011; Guo et al., 2012; Li et al., 2012; Zhao & Lucas, 2015). This section attempts to address this question by comparing the use of TT and CAT from several technical aspects. In the literature, the use of TT for H&S training is likely to have three major limitations, namely, limited representation of the actual workplace situations (Choudhry & Fang, 2008), limited consideration for workers who have low English proficiency (LEP) and low literacy (LL) (Choudhry & Fang, 2008), and failing to attract and maintain trainees' attention (Cherrett, Wills, Price, Maynard, & Dror, 2009). Instead, it is perceived that CAT can overcome the TT's limitations. More details of all these aspects are discussed in the following subsections.

5.1. Representing the actual workplace situations

TT training comprises both on-site and off-site programmes (Guo et al., 2017). On-site programmes directly expose trainees to real hazards and interfere with the construction progress by allowing trainees develop hands-on practices with workplace resources such as hand tools and machinery (Guo et al., 2012; Li et al., 2015). To overcome these issues, managers would rather arrange off-site training: workers are trained by attending workshops and memorising safety-related material written using technical jargon (Guo et al., 2012). So that workers can return to work as soon as possible, these training sessions are short duration (Guo et al., 2012). It is argued that knowledge learned in this way is impractical. Behzadan et al. (2011) pointed out that TT training often fails to prepare learners to effectively deal with the complexities of construction projects. “Workers may memorize a regulation and safety knowledge but find difficulties when they need to apply the knowledge in a real life situation”, (Li et al., 2012, p. 500). To take an example from a Hong Kong-based study, an interviewed worker stated that TT training was a waste of time because it did not provide a realistic sense of the actual workplace situations, and working on real construction sites was entirely different to how they were trained (Choudhry & Fang, 2008). Site conditions are complex and usually vary too fast with respect to weather, temperature, heat, humidity, and housekeeping for workers to apply theoretical H&S knowledge they have learned (Choudhry & Fang, 2008).

The expressive ability of TT is insufficient to fully showcase hazardous scenes to trainees (Li et al., 2012). Hazards can be better explained by using visual aids (Feng, González, Ma, Al-Adhami, & Mourgues, 2018b; Zhao & Lucas, 2015). Researchers are able to employ a range of techniques to give accurate representations of physical properties with CAT solutions (e.g., 3D Warehouse, Laser Scanner, BIM Toolkits, Autodesk Recap, and 360 Camera) (Höllerer, Feiner, Terauchi, Rashid, & Hallaway, 1999; Seth, Vance, & Oliver, 2011). It has been further pointed out by some researchers that the use of CAT allows simulation of actual site conditions by generating a close-to-reality virtual environment that contains “natural” details, such as certain spatial conditions (location) (Newton et al., 2013), certain environmental conditions (wind vectors, humidity, cloud coverage, temperature, dust, noise, etc.) (Helbig et al., 2014), inclement weather conditions (wet-weather, precipitation, heavy snow, etc.) (Wang & Dunston, 2007), certain thermal conditions (heated surfaces, smoky, hazy, etc.) (Bliss, Tidwell, & Guest, 1997), and certain housekeeping conditions (material storage, waste storage, etc.) (Li et al., 2012).

CAT techniques enable trainees to experience accidents and develop skills in realistic scenarios that represent the actual site conditions, which is considered a form of training aid with better efficiency than TT (Bosché et al., 2015; Dawood et al., 2014). Two studies included in this review have provided evidence in support of this view. Sacks et al. (2013) conducted a contrast experiment to compare the use of VR and TT for construction H&S training. They found that participants in the VR training group, who reported on average a higher rating on the question ‘To what extent was your feeling strong that the demonstrations represent real situations in construction sites?’ (VR group: 4.2, TT group: 3.8), had on average a higher score on the H&S knowledge test (VR group: 13.08, TT group: 11.17). The study by Chen et al. (2013) showed that 94% of the participants believed that the contents in the SG platform could represent their workplace situations and felt that their safety awareness had been enhanced after trying.

5.2. Text-free interfaces

Loosemore and Andonakis (2007) point out that the construction sector workforce tends to have on average a lower educational attainment compared to other industries. In the US, according to an industrial survey by National Safety Council in 2003, more than 70% of the construction workforce had LEP issues (Vazquez & Stalnaker, 2004). In NZ, 7,485 Asian workers (who might have LEP and LL issues) representing almost 5% of the whole workforce, were employed in the construction sector in 2013 (NZ.Stat, 2013). TT approaches rely heavily on paper-based materials and textual descriptions and therefore require trainees to be literate; having LEP and LL issues could lead to an individual having difficulties in acquiring H&S knowledge (Wallerstein, 1992). For example, a study of construction workers in Hong Kong revealed that uneducated workers could not read safety materials and had difficulties reporting and communicating during safety meetings (Choudhry & Fang, 2008). This highlights the importance of developing fair training for LEP and LL workers. It is argued that the use of CAT approaches can reduce language issues for LEP and LL workers during training because in the virtual environment only a few texts are included (Gao et al., 2017). Lin, Migliaccio, Azari, Lee, and De La Llata (2012) further pointed out that:

Using 3D simulated virtual job sites in safety training is expected to reduce the required level of language proficiency and literacy, and increase the understanding as well as learning interests of those in construction who can't speak or read much English (p. 113).

For the above reasons, it appears that CAT approaches may be superior to TT approaches in the effective transfer of training contents to LEP and LL workers. The evidence appears in one study included in this review to support this point of view. Greuter and Tepe (2013) developed a test to evaluate whether playing an educational game can help LEP learners attain H&S knowledge. In their study, a cohort of 24 participants for whom English was the second language responded positively that: 1. the gaming approach produced an easier learning experience for them than attending lectures because few texts were contained in the game environment; 2. the gaming approach was successful in assisting them in understanding the training contents; and 3. about 95% of the participants agreed that they learned a fair amount of hazard identification and prevention knowledge from the game.

5.3. User engagement

User engagement is the catalyst to the success of training programmes (Liaw et al., 2012). TT approaches are not engaging and trainees' attention is often poor at best (Cherrett et al., 2009; Harfield et al., 2007; Jeelani et al., 2017). For example, in the study by Rowland, Watson, and Wishart (2006), 91% of the participants thought that in-class instruction was a boring type of training and they did not want to complete the whole training programme. It is argued that the use of CAT approaches can help increase trainees' learning interests (Leong et al., 2013; Lin et al., 2011; Pereira et al., 2018). For example, in the study by Li et al. (2015), 70% of the participants reported that the CGS training platform helped them maintain high levels of engagement in the learning process. It is further implied that CAT approaches can immerse users by providing three major elements: presence, flow, and character identification (Bachen, Hernández-Ramos, Raphael, & Waldron, 2016; Girard, Ecalle, & Magnan, 2013; Newton et al., 2013; Sacks et al., 2013; Wang & Dunston, 2007). Presence is the mental experience occurring when a person is psychologically involved in a virtual environment (Bachen et al., 2016). Flow is the psychological sensation of losing track of time experienced by individuals who are busy responding to challenges that largely examine their stored knowledge (Bachen et al., 2016). Character identification is the instinctive reaction of individuals to assume as personal attributes the identities and goals of avatars in the virtual environment (Bachen et al., 2016). In particular, the nature of presence can arouse a frightening degree of sense (e.g., 'it can happen to you'), which ensures that a participatory response in the virtual environment is as close as possible to a natural response in real-life situations (Sacks et al., 2015; Zhao & Lucas, 2015).

Higher user engagement can lead to better learning outcomes (Greuter & Tepe, 2013). Given the above, it seems reasonable to expect that CAT approaches may be superior to TT approaches in sustaining learners' attention so as to promote the training efficiency. One study included in this review has presented evidence in support of this view. The study by Sacks et al. (2013) revealed that the participants in the VR training group, who scored on average higher on the question 'Did you feel you were concentrating?' (VR group: 4.2, TT group: 3.4), exhibited on average a higher level of H&S knowledge acquisition than the TT training group (VR group: 13.08, TT group: 11.17).

6. Conclusion

This study presents a review of existing publications on the use of TT and CAT for construction H&S training, with a view to providing insights into the effectiveness of TT and CAT as training tools.

In this review, we found that measures for effectiveness included knowledge acquisition, unsafe behaviour alteration, and injury rate reduction. In general, the results show a learning gain in trainees' knowledge acquisition, behaviour alteration and injury rate reduction with the use of TT techniques (see Section 4.2.4.2). However, the empirical evidence to support the effectiveness of CAT techniques is still rather limited. First, based on the findings from the systematic review, only one CAT study presented an evaluation of effectiveness in terms of knowledge acquisition, and there is a clear lack of evidence indicating the effectiveness of CAT techniques in promoting behaviour alteration and injury rate reduction (see Section 4.2.4.2). Second, it was observed that previous studies did not provide adequate evidence to prove the effectiveness of all CAT techniques. As mentioned in Section 4.2.1, five different techniques have been used in CAT studies to deliver construction H&S training, namely, SG, CGS, VR, AR, and MR. However, only the evidence for the effectiveness of VR can be observed in the existing literature (see Section 4.2.4.2), and data on SG, CGS, AR, and MR are not available at this point. Therefore, we cannot confidently argue that the use of CAT is more effective than TT given the limited evidence provided. Nevertheless, the improvements in trainees' knowledge acquisition by using CAT cannot be neglected as evidenced in Table 2. This is the main contribution of this paper as the effectiveness of TT and CAT was not uncovered in previous review studies in this field. This also opens up future research directions, suggesting that research is needed to provide empirical evidence on: 1. the effectiveness of CAT techniques in promoting behaviour alteration and injury rate reduction; and 2. the effectiveness of SG, CGS, AR, and MR approaches.

In addition to the lack of adequate evidence for the effectiveness of CAT techniques, another relevant issue is that some of the CAT studies (e.g., Jeelani et al., 2017) were based on small samples, recruiting fewer than ten participants (see Section 4.2.3.1). A number of researchers have pointed out that a sample size less than ten is not necessarily large enough to ensure validity of the results (Lachin, 1981; Ramakrishnan, Dell, & Holleran, 2002). Therefore, we recommend that further research on the effectiveness of CAT techniques may consider gathering data from large samples.

The review also uncovered a number of publications that evaluated the effectiveness of TT and CAT techniques in promoting trainees' knowledge acquisition. Among these studies, we found that trainees' knowledge level was all assessed immediately after training (see Section 4.2.4.1). In addition to immediate acquisition of knowledge, retention of the acquired knowledge in the long term is also critical in determining the effectiveness of a training technique (Papastergiou, 2009). For example, if the effect on trainees' knowledge acquisition retains for a follow-up of six months. Given this limitation, it will be useful for future research to employ longitudinal designs to repeatedly assess trainees' knowledge level in different phases (i.e. before training, immediately after training, and at a follow-up period after training), and then to provide evidence for the effect of TT and CAT techniques on both trainees' immediate knowledge acquisition and knowledge retention in the long term.

Further, a comparison between the technical characteristics of TT and CAT was performed in this review (see Section 5). We found that CAT techniques seem to make a greater contribution to trainees' learning process by demonstrating the following advantages over TT techniques: representing the actual workplace situations, providing text-free interfaces, and having better user engagement. Such findings could have practical implications for the construction sector by providing a clear comparison between TT and CAT techniques to help organisations be more systematic and rational in decision making regarding which technique to use.

Declarations of interest

None.

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