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Review

A Review of Virtual and Mixed Reality Applications in Construction Safety Literature

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Abstract: Over the last decade, researchers have used virtual- and mixed-reality (VR-MR) techniques for various safety-related applications such as training, hazard monitoring, and preconstruction planning. This paper reviews the recent trends in virtual- and mixed-reality applications in construction safety, explicitly focusing on virtual-reality and mixed-reality techniques as the two major types of computer-generated simulated experiences. Following a systematic literature assessment methodology, this study summarizes the results of articles that have been published over the last decade and illustrates the research trends of virtual- and mixed-reality applications in construction safety while focusing on the technological components of individual studies.

Keywords: construction safety; virtual reality (VR); mixed reality (MR); augmented reality (AR); augmented virtuality (AV)

1. Introduction

Injuries in construction occur at higher rates compared to many other job sectors, resulting in the loss of lives and profits [1]. Researchers have studied the root causes of accidents, as well as the current training practices in place, painting a dim picture of the effectiveness of current safety interventions [2]. To curb the rate of injuries, academics have called for increased research into the best methods for translating safety knowledge to construction workers. Due to the apparent ineffectiveness of current safety practices, academic studies have explored the use of innovative intervention methods offered through Virtual Reality (VR) and Mixed Reality (MR) techniques [3,4]. In such environments, users can easily and repeatedly experience spatiotemporal occasions that were previously impossible, dangerous, hard, or expensive to experience otherwise [4]. VR and MR incorporate multiple layers of information-such as BIM (Building Information Modelling), real-time geographical location, and audio alerts to create information-rich experiences conducive to innovative construction safety interventions. VR and MR techniques are specifically being deployed to aid in the transfer of knowledge to workers, to actively warn them of site hazards, and to pre-emptively eliminate hazards during preconstruction planning.

VR-MR platforms have been successfully implemented across various sectors, including the military, aviation, and medicine [5,6]. VR-MR systems are also being developed and evaluated in the field of construction as well. Within the field of Architecture, Engineering, and Construction (AEC), VR-MR systems have been developed to help professionals make more informed decisions and to enhance coordination amongst disciplines. For example, AR can allow users to see the location of columns behind a finished wall or the location of rebars inside of a column [7]. Architectural firms have used VR for marketing, and construction firms for scheduling and coordination, along with other applications [8]. The various uses of VR-MR have been long recognized in the AEC industry, and costs are rapidly decreasing [9]. Immersion hardware is getting better, offering a large field-of-view, high refresh rates, accurate point-of-view tracking; these benefits are possible at lower costs than in the past, mainly because VR-MR systems are gaining traction in the mainstream gaming community [9]. Investment in VR-MR technology is increasing, and the VR-MR market is projected to increase from $2.67 billion in 2015 to $66.68 billion by 2022 [10].

This study analyses the current trends in virtual- and mixed-reality applications in construction safety, particularly focusing on virtual-reality and mixed-reality platforms as the two major types of computer-generated simulated experiences. This study also focuses on the technological components of those VR-MR studies and discusses individual examples of research projects that implemented such technologies for construction safety application. A few scholars have published review articles of digital visualization techniques for safety applications. Zhou et al. [11] conducted a review of advanced technology for safety. Bhoir and Esmaeili [12] explored VR environments for safety; Guo et al. [13] looked at visualization technologies for safety. Li et al. [14] reviewed virtual and augmented reality systems for safety. Unlike other reviews, this study asks specific research questions through a systematic review technique and individually discusses the papers within the context of different safety applications, as well as their technological components. Moreover, by intentionally limiting the scope of the review to VR and MR, this study can highlight interactive safety interventions with detailed summaries of application areas, while separating VR and MR from the larger, general field of BIM (Building Information Modeling), 4D CAD (Computer-Aided Design), and other visualization technologies. The significance of this research lies in that it presents the application status of VR and MR in enhancing safety in the construction domain and brings more attention to these promising technologies and ultimately improves safety in the construction domain. The expected outcome of this content-analysis-based review can benefit both industry professional and researchers who find it necessary to design and develop an efficient application employing VR/MR technologies to enhance safety processes in the construction domain.

2. VR-MR Definition

It is important to clearly define the difference between VR and MR. Milgram [15] published an influential paper which delineates VR and MR. According to Milgram [15], there is a spectrum that spans between reality and virtuality. Reality consists of real objects, while virtuality consists of purely virtual objects, generated through computer graphic simulation. Augmented Reality (AR) occurs when virtual objects, text, or video are augmented onto a real scene. In other words, AR is "any technology that inserts digital interfaces into the real world" [16]. Augmented Virtuality (AV) sits within the spectrum of MR and is achieved when virtual representations are augmented on reality [15]. In some cases, distinguishing between VR and MR can be difficult. Milgram [15] states that "the most straightforward way to view a Mixed Reality environment is one in which real-world and virtual-world objects are presented together within a single display, that is, anywhere between the extrema of the virtuality continuum." Figure 1 illustrates Milgram's MR spectrum; the large blue area represents the span of mixed-reality classifications. Throughout this paper, "MR" will be used to describe the spectrum that exists between reality and digital virtuality, including both AR and AV technologies. On the opposite end of the spectrum from AR, and outside the spectrum of MR, sits the technology known as Virtual Reality (VR). VR "uses computers, software, and peripheral hardware to generate a simulated environment for its user" [3]. This paper contributes to identifying the recent employment areas of VR and MR technologies in construction safety academic literature, the analysis of their trend of application, specific safety purposes, safety application objectives, types of hazards addressed, and the hardware and software employed to develop such environments. Such contribution can benefit both industry and academia to understand the design and development requirements and components of VR/MR technologies for successful integration and safety enhancement in the construction domain.

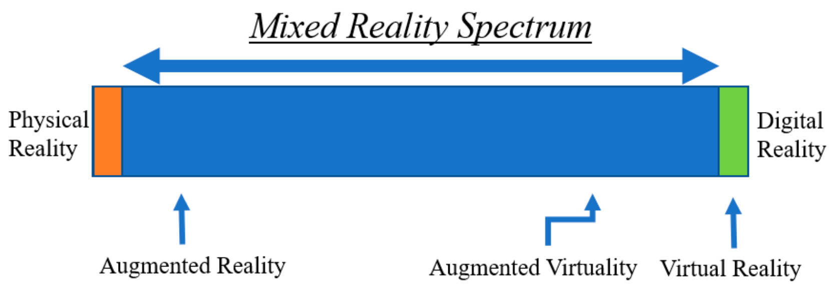

Figure 1. The Mixed-Reality Spectrum, adapted from Milgram [14].

3. Research Methodology

The literature review methodology follows the systematic principles presented by Denyer and Tranfield [17]. The methodology utilizes a five-step process: (1) formulating questions, (2) locating studies, (3) selecting questions, (4) analysis and synthesis, and (5) reporting results. Denyer and Tranfield's [17] methodology was implemented by academics from the fields of AEC [18,19], supply chain management [20], and energy management [21]. The systematic review methodology was developed to identify and evaluate completed studies and report pieces of evidence which produce clear conclusions [16]. For this review study, the same systematic process and steps were implemented. The objective was to identify the research trends of VR-MR applications for safety in the construction industry. To direct this objective, the following research questions were formulated and applied to each publication identified:

- Research Question 1 (RQ1): What is the status of VR-MR systems in construction safety academic literature?
- Research Question 2 (RQ2): What are the specific safety purposes of VR-MR systems in construction safety academic literature?
- Research Question 3 (RQ3): What are the safety application objectives of the VR-MR systems in construction safety academic literature?
- Research Question 4 (RQ4): Which hazards are addressed by VR-MR systems in construction safety academic literature?
- Research Question 5 (RQ5): What types of VR-MR systems are being used in construction safety literature?
- Research Question 6 (RQ6): What hardware and software tools are used to experience and develop VR-MR systems in construction safety academic literature?

To address the research questions of this paper, peer-reviewed bibliographic databases were investigated using a three-step process: (1) exploratory search, (2) systematic selection, and (3) classification. First, an iterative search was performed and the topics associated with VR-MR applications for construction safety were explored. Step one established a set of keywords to constrain result topics to be related to VR-MR applications for safety. Following the same boundaries from step one, iterations of keywords were used to search academic databases and perform a criteria-based literature selection. In step three, the researchers categorized and organized the papers selected to zero-in exclusively on the trends of VR-MR for construction safety. The collected literature was then analyzed and discussed to present an up-to-date illustration of VR-MR for construction safety.

3.1. Literature Search and Selection

To locate publications related to VR-MR for construction safety, a set of keywords were entered into literature databases to obtain relevant articles and eliminate all irrelevant results. Three distinct filters were deployed to narrow the search results content systematically. The filters were explicitly designed for title, abstract, body of article, and publication year. Collectively, the filters were utilized to identify the proper publications.

The first filter was applied to delineate the overall topic of this review: construction safety. Hence, the keywords "construction" and "safety" were chosen as classifiers found in the title or abstract of the publications. The second filter was then used to define the characteristics presented in the title, abstract, or body of the papers.

An exploratory web search revealed four significant classifiers related to innovative, interactive computer-generated simulated safety interventions: "virtual", "augmented", "mixed", and "reality". These four keywords were applied in the second filter to reflect the scope of this review accurately. Finally, a third filter was applied to restrict the publication date. Articles published from 2007 to 2018 were considered to ensure contemporaneity of the research contained within this review.

The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) (Moher et al., [22]) procedure was followed to document this procedure (see Figure 2). In the identification stage, 114 potentially relevant articles were identified. After the screening the process, duplicate records and articles that were not published between 2007 and 2018 or the ones that were not directly related to construction safety were identified and excluded. Next, the full text of the publications were reviewed to ascertain if they directly applied VR or MR to construction safety and at least one of the research questions of this paper were discussed in their content. Forty-six publications were identified after the incremental evaluation.

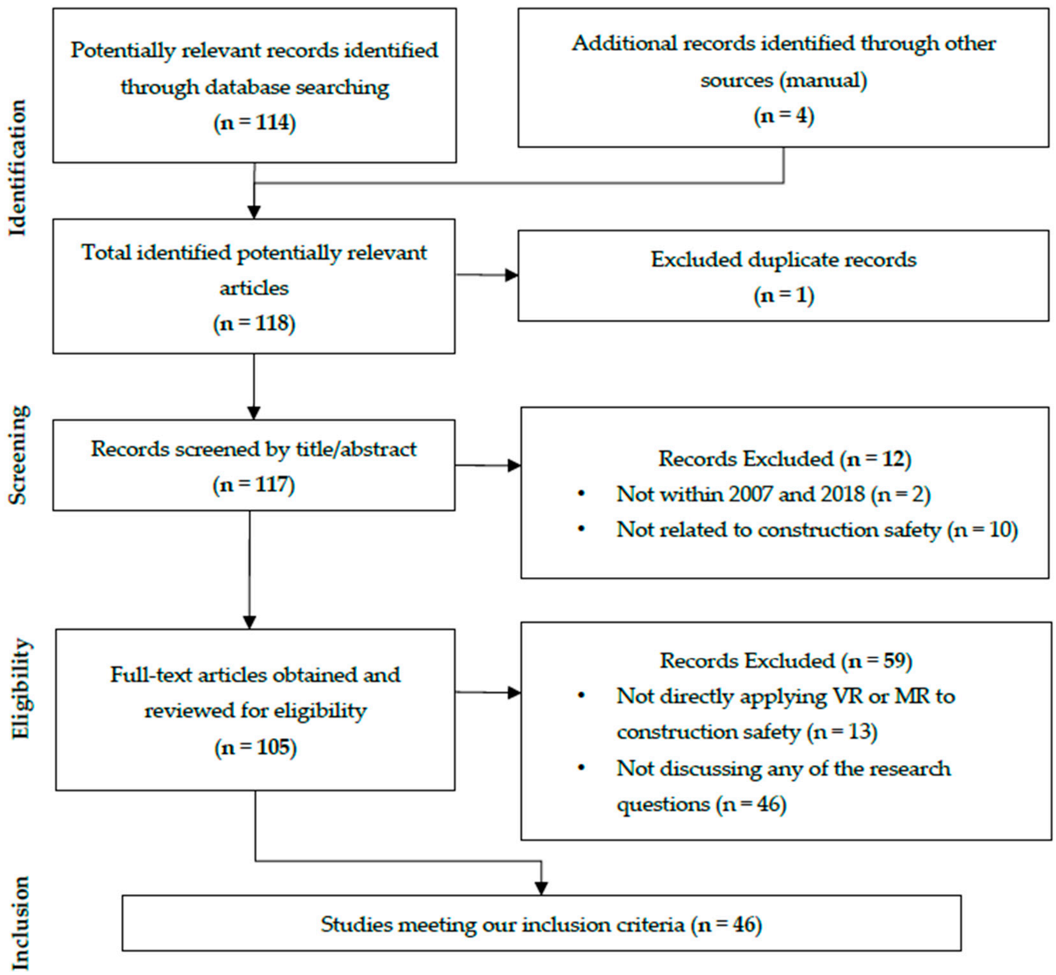

Figure 2. Literature selection following Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines.

3.2. Literature Classification

The 46 studies identified via the literature selection process were systematically sorted in order to segregate the publication content and to facilitate data interpretation. This categorical sorting was performed for each study following the criteria and questions illustrated in Table 1. The results section discusses the outcome of the collected data for each of these research questions.

Table 1. Analysis criteria for each of the proposed research questions (RQ).

RQ1	RQ2	RQ3	RQ4	RQ5	RQ6
Status	**Safety-Related Purpose**	**Safety Application Objective**	**Hazard Types**	**System Type**	**Hardware and Software**
Number of publications	Education and Training	Hazard Identification	General Safety	Virtual Reality	Peripheral Hardware
Publication year	Monitoring On-Site Environment	Hazard Avoidance	Struck-by and Caught-in	Augmented Reality	Development Software
Publication Source	Preconstruction Planning	Hazard Response and Communication	Fall	Augmented Virtuality	
Publication author(s)		Heavy Equipment Training	Electrical	Mixed Reality	

4. Results

4.1. RQ1: Status of VR-MR Systems for Construction Safety

The 46 VR-MR publications were analysed to determine the status of the subject in academia (RQ1). The number of publications per year has fluctuated over the last decade. The first five years (2007–2012) present a low number of articles (average: 1.7/year), with zero relevant publications in 2008 and 2010. In 2011, it appears that the subject began to gain attention, with the number of publications up from zero to four over the previous year. Since 2011, at least three papers have been published on VR-MR for safety each year. During the past six years (2013–2018), the average of publications per year was six. The number of publications with corresponding year range is illustrated in Figure 3.

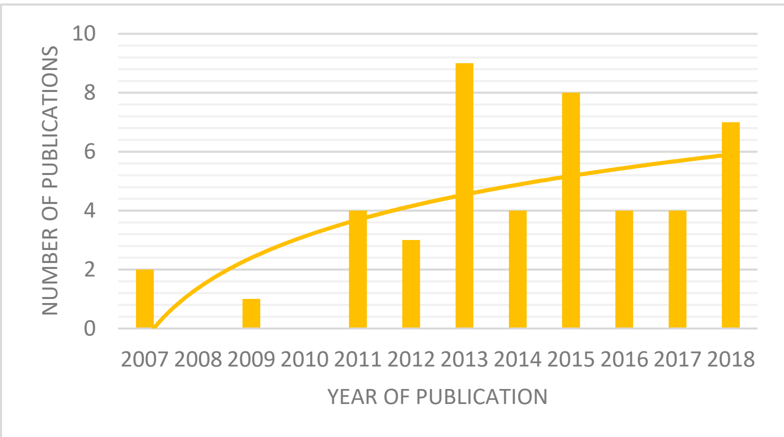

Figure 3. Number of publications on virtual- and mixed-reality (VR-MR) for construction safety 2007–2018.

The number of publications within their corresponding year range were then organized for each specific journal and conference. Table 2 itemizes the journals and conferences with at least two publications of VR-MR applications for safety over the last decade. For journal publications, *Automation in Construction* has published the largest number of papers on the topic of VR-MR for construction safety (21.7%), followed by the *Journal of Computing in Civil Engineering* (10.9%), *Construction Research Congress* (8.7%), and the *Journal of Information Technology in Construction* and *Safety Science* (each with 6.5%). This distribution indicates that most VR-MR construction safety applications were published in technology-related AEC journals.

Table 2. Number of publications by journal or conference with year range.

Journal or Conference	Year Range	Number of Publications
Automation in Construction (ELSEVIER)	2011–2018	10
Journal of Computing in Civil Engineering (ASCE)	2012–2017	5
Construction Research Congress (ASCE)	2014–2018	4
Journal of Information Technology in Construction (ITcon)	2007–2011	3
Safety Science (ELSEVIER)	2014–2016	3
Other	2007–2018	21
Total	2007–2018	46

The publication titles were assessed and the most common words in them were, predictably, "construction" (65%) and "safety" (65%). "Virtual" (39%) and "reality" (33%) were also prominent, reflecting the fact that VR was more often used than MR for construction safety applications. "Education" (15%) and "training" (33%) were also widely used terms in the titles, reflecting the most common purpose of VR-MR in construction safety. Additionally, the most prevalent researchers of VR-MR for safety were identified (Table 3). Researchers *Li*, *H.* (Hong Kong Polytechnic University), *Chan*, *G.* (Hong Kong Polytechnic University), *Skitmore*, *M.* (Queensland University of Technology) and *Fang*, *Y* (Monash University) are major contributors of knowledge on the subject. The author with the largest number of publications, *Li*, *H.*, has seven articles that are related to VR-MR construction safety applications from 2012 to 2015. His research encompasses VR and AR technologies, exploring safety training, real-time site monitoring, and educational games. As a single author, Li, H. well represents the spectrum of VR-MR studies related to construction safety. The top six authors contributing to the study of VR-MR for construction safety often collaborated, and each addressed hazard identification among other safety application objectives (see Table 3). Countries that conducted relevant research were also assessed in this part of the study (see Figure 4). The United States has the most research studies with 22 publications, followed by Australia (10), South Korea (8), and Hong Kong (8).

Table 3. Top six contributing authors.

Author	Institution (Country)	# of Publications	Safety Application Objectives
Li, H	Hong Kong Polytechnic University	7	Hazard Identification; Hazard Avoidance; Heavy Equipment Safety; Hazard Response and Communication
Chan, G.	Hong Kong Polytechnic University	5	Hazard Identification; Hazard Avoidance; Heavy Equipment Safety
Skitmore, M.	Queensland University of Technology (Australia)	4	Hazard Identification; Hazard Avoidance; Heavy Equipment Safety
Fang, Y.	Monash University (Australia)	4	Hazard Identification; Hazard Avoidance; Heavy Equipment Safety
Sacks, R.	Technion-Israel Institute of Technology	3	Hazard Identification; Hazard Response and Communication
Teizer, J.	Georgia Institute of Technology (USA)	3	Hazard Identification; Hazard Avoidance; Heavy Equipment Safety

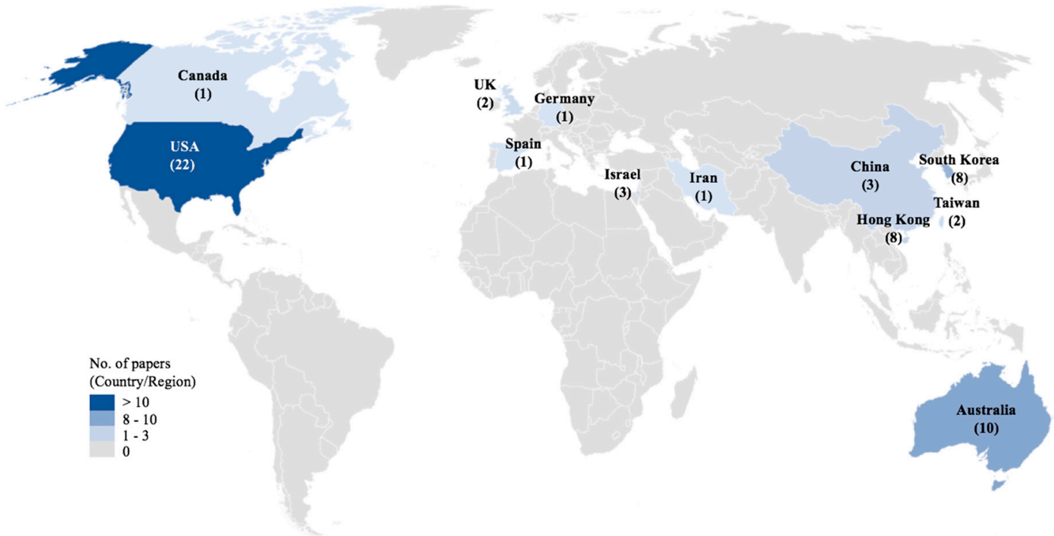

Figure 4. Map of publications.

4.2. RQ2: Purpose of VR-MR Systems for Construction Safety

The 46 VR-MR publications were analysed to determine the safety purpose of the study (RQ3). The purpose of each article fell into the following three groups, directly related to safety: (1) education and training, (2) monitoring on-site environment, or (3) preconstruction planning. The classifications are not mutually exclusive; several researchers combined multiple purposes together. The publications most commonly addressed education and training (37, 80.4%), followed by monitoring the on-site environment (11, 23.91%), and lastly, VR-MR was leveraged as a preconstruction safety planning tool (4, 9%). A single publication focused on tele-operation of cranes and did not fall within the listed categories [23]. The training and education of workers, managers, and students was the most common purpose of the VR-MR studies reviewed. VR and MR has a demonstrated potential to provide training for dangerous fields of work, allowing users to simulate tasks while avoiding exposure to chaotic jobsites [6]. VR-MR systems were designed as serious games in 8 out of the 32 training and education studies. For example, Li et al. [24] developed a multiuser VR training program in which users were using a Wii game controller in order to learn and practice safe crane dismantling procedures. An experiment compared inexperienced trainees using the VR training environment to more experienced workers and those trained via traditional methods, with favourable results for the VR users [24]. Similarly, Guo et al. [25] developed a highly collaborative VR game that allowed several users trainees to perform construction operations within a virtual environment. The web-based platform focused on specific construction operations, specifically activities associated to mobile and tower cranes and pile drivers. The researchers stressed the importance of being able to interact and collaborate with the game and other trainees. In another example, Dickinson et al. [26] performed an experiment in a VR serious game focused on trench safety, and specfifically on struck-by, fall, and caught-in hazards. Lin et al. [27] similarily developed a VR game designed to be immersive, interactive, and entertaining to test the hazad identifcation skills of the users. Pedro et al. [28] developed and tested an educational VR platform to teach students in the AEC field about the dangers of construction. Costs and time were stated as main challenges related to the development of the VR system. Due to these limitations, researchers are also investigating the use of 360 VR to simulate construction sites and safety challenges. A 360-degree VR delivers a panoramic view of a real-world environment with a high sense of presence (Bourke [29]). In contrast to traditional VR, 360 VR offers fast digital jobsite generation, easy to produce simulations, and high levels of realism due to the inherent photography techniques used in this technology. For instance, Pham et al. [30] developed a learning platform for improving safety education field trips using 360 VR. The preliminary results of this study showed that there were no significant differences between the students who used the 360 VR and those who visited the real site to identify the hazards. In another series of studies, Eiris et al. [31,32] developed a hazard identification training and assessment using 360 VR. Users in those studies found 360 VR advantageous for learning about hazard identification.

Monitoring the on-site environment for safety was the sole objective of 4 out of the 11 (36%) publications within the on-site monitoring category, while the remaining projects coupled on-site monitoring with safety training or preconstruction planning. On-site monitoring combines VR-MR systems with location trackers, providing valuable safety information to workers, often in real-time. For example, Kim et al. [33] developed an AR system that employed Google Glass technology and real-time tracking to augment the view of workers. Users were visually warned of approaching equipment and vice versa, equipment operators were warned of approaching workers. Cheng and Teizer [34] accessed the potential of VR technology combined with real-time tracking to improve situational awareness of construction workers. The authors used radio-frequency identification (RFID) tracking devices to monitor construction equipment and worker locations, displaying the information in a virtual environment. The prototype study showed positive results; the researchers believe such technology can help workers avoid hazardous situations and also train workers using "close call" simulations in the virtual world. Li et al. [35] focused on safety and efficiency training using VR and real-time tracking. Using RFIDs and pre-defined hazard zones, workers were warned with a "beep" from their hardhats when entering a dangerous area or the proximity of heavy machinery. Further, real-time locations of equipment and workers were represented virtually in what the researchers called the "Virtual Construction Simulation System", which could be monitored by managers and safety professionals. The researchers noted that the real-time data visualization only offers a limited level of realism and argued that AR is the future of construction training.

Preconstruction safety planning is an important preliminary action that can be taken to eliminate hazardous construction situations through proper design before the project begins. VR and MR systems have proved to be strong facilitators of the design-for-safety process. For example, Sacks et al. [35] used a Cave Automatic Virtual Environment (CAVE) that allowed construction managers and designers to view and discuss the safety implications of various designs. Other studies employed VR for preconstruction planning but did not include design professionals, leaving the safety planning to project managers and superintendents [36–38]. Thus, the approach was slightly different: planning for safety rather than designing for safety. In either case, virtual simulations of construction facilitated conversations about pre-emptive actions that could be taken to ensure a safe, accident-free jobsite.

4.3. RQ3: Application Objective of VR-MR Systems for Construction Safety

The 46 VR-MR publications were analysed to determine the aspect of safety that the technology proposed to improve (RQ4). Safety application objective means the safety issue that the author(s) aimed to address with VR-MR technology. After reviewing the 46 articles, four major categories emerged: (1) hazard identification, (2) hazard avoidance, (3) hazard response and communication and (4) heavy equipment safety. The categories are not mutually exclusive; several studies addressed multiple application objectives, resulting in total percentages reaching over 100% (see Table 4 below).

Table 4. Application objectives of VR-MR systems for construction safety.

Safety Application Objective	# (%) of Publications
Hazard Identification	26 (56.5%)
Hazard Avoidance	11 (23.9%)
Hazard Response & Communication	8 (17.4%)
Heavy Equipment Safety	7 (15.2%)
Other	5 (10.9%)

Hazard identification is described by Bhoir and Esmeili [12] as the "foundation of any construction safety program." Hazard identification is the ability to identify unsafe conditions and such scenarios should be dealt with in a proactive manner by management [39]. Zuluaga et al. [40] noted that "workers cannot judge how severe and probable risky situations are when the hazards themselves have not been identified in the first place." Despite hazard identification's noted importance for overall job site safety, Albert et al. [1] claimed that there is a dearth of strategies to properly train workers in hazard identification. Such training is not easily accomplished given the dynamic and ever-changing atmosphere of a construction site [6,41]. VR and MR systems can offer engaging ways to train workers, students, and managers in hazard identification. As an example, Lin et al. [27] published a study in which university students navigated a VR construction environment as "Safety Inspectors" tasked with identifying as many hazards as possible (e.g., unsafe material storage, uncapped rebar) within a time limit. Similarly, Zhao et al. [42] designed a VR system in which users performed a site survey with the goal to identify electrical hazards. Jeelani et al. [6] attributed poor hazard recognition levels to the pervasive use of ineffective and unengaging training practices. Jeelani et al. [6] used panoramic photographs and videos to create an AR training environment to engage and challenge users to properly identify hazards. In similar studies, Pham et al. [30] and Eiris et al. [31,32] used the power of 360 panoramic VR to create hazard identification training and an assessment environment which engage users in true-to-life simulations of construction jobsites.

Hazard avoidance VR-MR systems actively aided construction personnel to avoid dangerous areas on site. Hazard avoidance systems most often employed real-time tracking and would warn workers of hazardous areas or approaching equipment, differing from hazard identification platforms which focused on the personal development of identification skills. For example, Cheng and Teizer [34] developed a VR system which combined real-time tracking with virtual representations of workers and equipment to provide a picture of an active jobsite. The real-time information allowed users to avoid hazardous areas. Similarly, Li et al. [30] coupled sensors and warning tags installed in helmets to alert workers approaching hazardous areas or dangerous heavy equipment using an AR platform. Further, Li et al. [35] utilized VR to allow post-event analysis of near-miss incidents. With the ultimate goal of hazard avoidance through improving the situational awareness of workers, Fang et al. [43,44] created and tested an operator-assistance system for crane operators by leveraging real-time motion sensing and VR-assisted representation of dynamic workspace.

VR-MR systems were also used for hazard-response- and communication-related applications. If a hazard is properly identified on an active jobsite, the issue must be responded to appropriately and communicated with other workers in order to avoid an accident or further injury. As an example, Zhao and Lucas [45] designed a VR platform which addressed both hazard identification and response, specifically for electrical hazards. Through a virtual simulation, users were trained on safe emergency response procedures for people who come into contact with an electrical hazard. In another example, Park and Kim [37] utilized both VR and AR to test a system which communicated site hazards in real-time to workers through mobile phones. In another study, Shi et al. [46] utilized a multi-user VR system with motion tracking capabilities to enhance iron-workers interpersonal social interaction and communication simulating their work in high-rise buildings. In another recent study, Olorunfemi et al. [47] used a holographic MR technology that runs on Microsoft Hololens to better enable visual interaction and enhance remote collaboration for jobsite risk communication on the construction jobsites.

Heavy equipment on construction sites poses a unique set of safety hazards and few VR-MR platforms have been designed to train equipment operators on proper, safe practices. For example, an MR system tested by Segura et al. [48] provided a realistic excavator training environment while eliminating any real danger. Trainees entered into a real excavator cabin, while a unique HMD system, combined with a blue screen and cameras, allowed the user to simultaneously view a virtual construction site and also the real controls of the excavator cabin. An example of VR for heavy equipment safety, the researchers combined real-time tracking and BIM to create a virtual training environment for crane operators [43,44,49]. Within the VR system, a "close-to-reality experience" of lifting operations was provided. Further, the difficulty of the lifting scenarios could be increased as trainees progressed through the training.

4.4. RQ4: Hazard Categories Addressed in VR-MR Systems for Construction Safety

The 46 VR-MR publications were also analysed to determine the hazard category the system proposed to address (RQ4). VR-MR studies either sought to address a broad range of safety issues or focused on a specific category of hazards. According to the Occupational Safety and Health Administration (OSHA), there are four categories of hazards which cause the majority (64.2%) of construction fatalities [50]. The "focus four" hazard categories are: fall, struck-by, caught-in or -between, and electrocution. The 46 VR-MR studies reviewed heavily reflect this reality and mainly target on the focus four hazards defined by OSHA. Numerous VR-MR publications addressed general safety hazards, without singling out a specific hazard type. Aside from the broad category of "general safety", three specific hazard categories emerged: (1) struck-by and caught-in, (2) fall, and (3) electrical. The classifications are not mutually exclusive; several researchers addressed hazards across multiple categories, resulting in totalled percentages reaching over 100% (see Table 5 below). Although not the single leading cause of death in the construction industry, researchers most commonly targeted struck-by or caught-in hazards (45.6%). Struck-by or caught-in hazards often are associated with heavy equipment, a piece of technology that researchers have been able to compliment with digital interfaces such as tablets, which provide operators an additional layer of contextual information (e.g., Fang et al. [51]). The next most common focus was general safety (34.8%), followed by falls (28.3%), and lastly, electrical hazards (13%). Talmaki et al. [52] focused on the hazard of striking underground utilities and Lu and Davis [53] discussed the effects of noise on risk perception—the two publications are listed as "other" (4.3%).

Table 5. Hazard categories addressed by VR-MR system.

Hazard Category	# (%) of Publications
Struck-by or Caught-in	21 (45.6%)
General Safety	16 (34.8%)
Fall	13 (28.3%)
Electrical	6 (13.0%)
Other	2 (4.3%)

The categories of struck-by and caught-in are similar hazard types in that they are often caused by corresponding construction activities, especially the operation of heavy equipment such as cranes. For example, a rotating crane may pose a struck-by hazard for workers underneath the material load and simultaneously, a caught-in hazard for workers near the rotating equipment. Thus, the two hazard types are grouped into one category for the purpose of this review, as any study which focused on heavy equipment naturally addressed both struck-by and caught-in hazards, making distinguishing between the two irrelevant. Fang et al. [49] focused on struck-by and caught-in hazards using a VR platform. The study used ultra-wideband (UWB) tracking to warn crane operators of potential collisions with actual on-site objects. The researchers emphasized the importance of an accurate as-built virtual environment and the need to improve the situational awareness of heavy equipment operators. In more recent studies, they combined laser scan data, sensors, and a tablet computer to provide crane operators with real-time obstacle information using VR [43,44,51]. Park et al. [54] conducted early development of an AR system based around a transparent tower crane window where hazard information was augmented onto the crane window to assist crane operators to avoid striking objects or personnel.

The studies that addressed construction safety in general, targeting a multitude of hazards, were categorized under "general safety". As an example, Albert et al. [1] used AV to address general safety hazards. The researchers used a unique hazard categorization technique based on

10 energy sources: gravity, motion, mechanical, electrical, pressure, temperature, chemical, biological, radiation, and sound. The theory was that all hazardous scenarios in construction originate from one of these energy sources. The researchers tested the AV system and showed that crews could identify 46% of hazards prior to the intervention and 77% of hazards in the postintervention phase [1]. Goulding et al. [55] used theories from behavioural psychology to develop a VR game in which participants managed a construction site, with various hazard types present. The team recognized the capability of a VR experience to enhance knowledge transfer and retention, citing the Chinese proverb: "I hear and I forget, I see and I remember, I do and I understand" [55].

Fall accidents are the leading cause of death in construction [50]. One research project focused solely on fall hazards using an MR platform [56], while eight studies coupled falls with other hazards. For example, Teizer et al. [57] designed a VR worker training system for an especially dangerous construction activity: steel erection. Ironworkers face one of the highest fatality rates in construction, mostly due to falls [57]. The researchers coupled real-time tracking devices (UWB) with VR technology to train ironworkers in an indoor facility. The platform allowed for post-assessment analysis after each training session to allow users to learn from potentially hazardous actions. Li et al. [58] monitored the on-site environment using virtual objects and real-time tracking to address fall and struck-by hazards. Using predefined boundary boxes and digital danger zones, workers were warned whenever approaching an unprotected edge or opening.

Zhao and Lucas [45] developed a VR worker training system for an especially dangerous and invisible force: electricity. By leveraging VR, the researchers were able to simulate the effects of a deadly force—electricity—while also creating an active, engaging learnings scenario. Thirteen students tested the prototype and reported positive experiences. The researchers built off previous research [59] which discussed the concept of a serious game for VR training. Zhao et al. [59] designed a prototype in which participants navigated a virtual environment and "health points" could be lost through careless behaviour related to overhead powerlines and other electrocution hazards.

4.5. RQ5: Types of VR-MR Systems for Construction Safety

The 46 VR-MR publications were analysed to determine the system type deployed (RQ5). Two major technical categorizations emerged during the literature analysis: VR and MR. VR is the dominant system in the industry for safety. The majority of the 46 studies reviewed used VR (71.7%) compared to MR (23.9%), with two studies utilizing both technologies in conjunction (4.35%). Within the realm of MR, AR was used in five studies, AV in three studies, and the specific term "mixed reality" was used in two studies [48,56]. Both VR and MR have limitations. VR is cited as having high development costs [19,27,28], while MR faces the challenge of "drift" and the tracking of moving objects [60]. Figure 5 illustrates MR-VR examples for construction safety applications along the reality–virtuality spectrum.

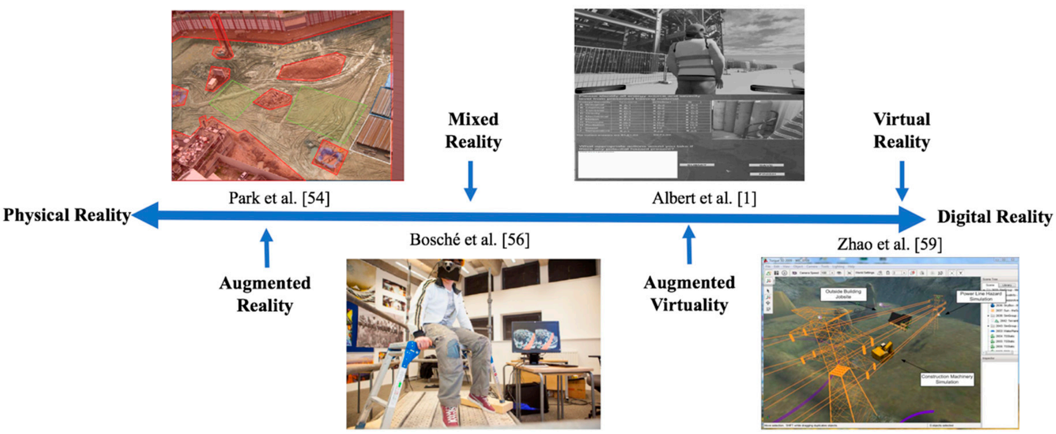

Figure 5. MR-VR examples for construction safety applications along the reality–virtuality spectrum.

VR is powerful in its ability to generate unlimited training scenarios [5]. For example (see Figure 5), trainees were able to virtually experience the dangers of confronting overhead powerlines and potential electrocution, without physically being exposed to real dangers [59]. Or, in another example, workers repeatedly dismantled a virtual crane to practice proper safety protocol, until the routine was safely committed to memory [24]. The adaptability of VR has allowed the technology to be incorporated in a variety of innovative safety interventions for construction.

Bosché et al. [56] serves as an illustrative example of MR for safety training. In the experiment, real world objects, such as beams and bricks, were combined with a 3D virtual environment that created the sensation of working at elevation (see Figure 5). The researchers noted that their system lay in the middle of the reality–virtuality spectrum. The system was designed to give participants a safe environment in which to work, for example, laying bricks on the ground level of the laboratory, while using a HMD (Head-Mounted Display) to provide the sensation of laying the bricks on an elevated surface. Within the spectrum of MR, Park et al. [54] experimented with AR to provide crane operators with more information while performing lifting operations. The proposed system was centred around a transparent Heads-Up Display (HUD) crane window onto which pertinent information could be augmented (see Figure 5). An example of AV (see Figure 5) comes from research by Albert et al. [1] which discussed the development of a system called System for Augmented Virtuality Environment Safety (SAVES). The researchers combined BIM with 700 construction images to create a serious game learning environment that taught hazard identification. Users increased their hazard identification score on average from 47% to 77% through the AV system.

4.6. RQ6: Hardware and Software of VR-MR Systems for Construction Safety

The 46 VR-MR publications were analysed to determine the peripheral hardware and development software used (RQ6). Virtual- and mixed-reality environments are generated by the interaction between three components: computers, software, and peripheral hardware [3]. The hardware is the key interaction point, connecting the user and the virtual or augmented world. The most immersive hardware options are HMD and CAVE [19]. Immersive training is an answer to issues voiced regarding the effectiveness of safety education in the industry described by Wilkins [2] and Zuluaga et al. [40], meaning HMD and CAVE hardware is advantageous. Table 6 lists the hardware categories with the corresponding number of publications. Most frequently (21, 45.7%), studies employed the traditional arrangement of the computer setting: using a monitor together with a mouse and keyboard to interact with the virtual environment. Such low-cost setups which are readily available and do not require purchasing expensive VR-only equipment that do not already come with most computers. Although not as immersive as HMD or CAVE environments, the simple set up using monitor, keyboard, and mouse is cost effective. Five studies (10.9%) extended this traditional arrangement by adding a game controller (e.g., a Wii controller) to facilitate interaction and navigation within the VR-MR environment. Mobile devices and tablets (7, 15.2%) were used to extend the VR-MR environment into the field, giving workers and managers access to safety information on the go. For the highest level of user immersion, HMD (11, 23.9%) and CAVE (3, 6.5%) were used. Such devices give the user a high sense of presence, compared to computer monitors. However, there are additional costs—both in hardware and development—related to HMD and CAVE technologies and thus, these are perhaps restrictive for some academic studies. It is worth noting that recently, ease of access to very low-cost solutions such as Google Cardboards has made experiencing immersive VR available to an even larger population. These VR cardboards usually have a very low cost, allowing scalable adoption by utilizing mobile phone technologies that are readily available to most users.

Table 6. Peripheral hardware used in VR-MR publications.

Type of Display/Input	# (%) of Publications
Monitor/Mouse-Keyboard	21 (45.7%)
HMD/Keyboard-Mouse-Gamepad-Motion Tracking	11 (23.9%)
Mobile Device and Tablets/Finger Touch	7 (15.2%)
Monitor/Game Controller	5 (10.9%)
CAVE/Keyboard-Mouse-Gamepad-Motion Tracking	3 (6.5%)
HUD/Motion Tracking	1 (2.2%)

Computer software is used to create simulations and digital elements, such as buildings and construction equipment. Software is a key development tool for both VR and MR applications. Some software are used to model a highly realistic virtual environment, while software known as game engines are used to develop games inclusive of the rendering, object creation, and system interaction [12]. The software packages utilized to develop the VR-MR platforms were numerous, with the game engine Unity 3D (30.4%) being the most commonly specified, followed by the modelling software Autodesk 3ds Max (17.4%) and Autodesk Revit (15.2%). Ten of the 46 publications (21.7%) did not list the software used. Table 7 shows the most common software specified. Publications often combined more than one software to develop the VR-MR platform.

Table 7. Software used in VR-MR publications.

Software	Year Range	# (%) of Publications
Unity 3D (Game Engine)	2012–2018	14 (30.4%)
Autodesk 3ds Max	2009–2017	8 (17.4%)
Autodesk Revit	2011–2017	7 (15.2%)
Torque 3D (Game Engine)	2009–2016	4 (8.7%)
Autodesk MAYA (Game Engine)	2011–2015	4 (8.7%)
Trimble Sketchup and 3D Warehouse	2013–2017	3 (6.5%)
Microsoft XNA Game Studio (Game Engine)	2011–2013	3 (6.5%)
3DVIA Virtools (Game Engine)	2012	2 (4.3%)
Not listed	-	10 (21.7%)

5. Conclusions

This review paper provides a thorough analysis of contemporary publications by scholars related to VR-MR for construction safety, as well as specific examples illustrating current research trends. The status of VR-MR for safety was illustrated through a systematic analysis of published literature on the topic. VR is the most dominant system type (compared to technologies falling within the MR spectrum), despite cited issues of computational cost and development time. Education and training is the most common purpose of the VR-MR for safety applications, and the majority of researchers applied VR-MR technology as a tool for improving hazard identification skills, followed by hazard avoidance and hazard response and communication. The most common hazard category addressed was struck-by and caught-in, followed by general safety and fall hazards. The majority of researchers used computer monitors and keyboards for system interaction, choosing this low-cost commonly available peripheral hardware over more immersive options such as HMDs of CAVEs. Unity 3D game engine was the most commonly used software to create VR-MR for safety applications.

In the foreseeable future, VR-MR for construction safety will continue to be a subject of research in the construction industry. The large moral and financial burden caused by construction accidents, coupled with the dangers of on-site safety training, demand innovative new approaches to safety. The studies varied in objective, technology, and scope, yet the studies consistently reported positive results from safety interventions using VR-MR systems. Further studies should be conducted to quantify direct impact on accident reduction, to analyse the long-term learning effects of VR-MR safety training platforms, and to address the computational and cost limitations of VR-MR development.

As technology advances, more realistic and personalized training interventions can help workers properly identify and remedy on-site hazards and have improved situational awareness. Using low-cost VR platforms (e.g., Google Cardboards), can democratize safety education and make it available to a larger population. With progress and further research, injuries and deaths in construction might be reduced through VR-MR technologies. It is worth noting that this review paper only focuses on the research articles published in the peer-reviewed journals and conference proceedings to illustrate the state-of-the-art of VR-MR applications for construction safety. Building on the outcomes of this literature review and to capture the state-of-the-practice, other studies should be conducted using review, survey, or interview techniques and targeting construction professionals to investigate how they use VR-MR for safety purposes.

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