Virtual Reality (VR): A Review on its Application in Construction Safety

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Article History: Received: 11 January 2021; Revised: 12 February 2021; Accepted: 27 March 2021; Published online: 10 May 2021

Abstract: Technology has made workplaces safer and more effective. It has allowed us to increase efficiency, strengthen cooperation, and tackle more complex projects. Visualization technology application has established that simulated 3D site models have a strong ability to facilitate hazard identification and the cognition of worker's risk. Virtual Reality (VR) is one of the commonly recognized innovations that helps reduce the number of accidents in the workplace. Thus, this paper comprehensively discusses VR technology's role in construction safety achieved through a profound review of its applications, evolutions, and the challenges it imposes with its utilization. It is in line with the objectives of conducting an in-depth study of VR to address the knowledge gap that introduces these advanced technologies, such as providing sensitive information regarding its general concept, beneficial applications, and possible limitations. Like any technological advancement, the VR application still poses several challenges that are yet to be unraveled. Future study is expected to consider 1) inaccuracy between the user's actual movement and the virtual animation; 2) offering limited scope, therefore, overlooking other relevant factors; 3) work-intensiveness, relatively high cost and maintenance; and 4) technical complexity. Researchers recommended being considered for results are reviews based on their perspectives on its applications.

Keywords: Virtual Reality (VR), VR application; construction safety; safety management; review

1. Introduction

The generally hazardous and unsafe environment that construction processes are usually immersed in [1], [2] makes its workforce safety one of the principal concerns worldwide [3]. And it indicated that compared to other occupational sectors, accidents in the construction industry take place to a higher degree, resulting in injuries, deaths, and revenue shortfall [4]. This claim was also supported by Wu and Fang, who further elaborated that this is a case experienced to a global extent [5]. Zhang et al. noted that the official database reveals that during the period between 1989 to 2013, over 26 000 workers assigned to construction jobs were reported to die under the site location [6]. Besides, the International Labor Organization (ILO) also said in 2005 that, considering worldwide records, the number of fatal incidents in construction sites reached approximately 60,000 cases annually [7]. Despite this alarming condition of construction safety worldwide, efforts in improving this subject were found to decrease since 1992, and that there is a "need for new and innovative safety practices" [8]. Correspondingly, it emphasized that even with the presence of rigorous safety and health protocols, "no significant decline in the number of construction accidents has been recorded" [9]. The same assertion was also reflected in Huang and Hinze (2006) statement, conveying that the construction industry's safety records remain one of the most unsatisfactory [10].

The construction industry is distinguished as a cynical sector for implementing advanced technologies in their regular practices [11], [12]. This hesitation is due to two primary reasons identified by Mitropoulos and Tatum (2000): 1) ambiguity in the application of modern technologies and 2) inadequate knowledge and awareness of technology concepts and their benefits [13]. However, alongside the global impact of technologies on almost every aspect of living, researchers have gradually embraced technology's adoption to advance construction safety practices and amend existing safety programs through a profound and palpable evaluation of its domain [1]. Akinlolu et al. (2020) affirmed in a study that the application of broad and various technological innovations in on-site safety and health management had experienced a rap growth during the previous years. Numerous studies have been published concerning this timely and relevant subject, paving a broader path for boundless research opportunities [14]. Thus, as Zhou et al. and Li et al. argued, a review of these studies will be very significant for construction practitioners to thoroughly grasp and eventually integrate research potentials into their efforts in promoting safety and health management in the construction workplace [1], [2], [15].

One of these advancements that have been presently creating a highly regarded name is virtual reality (VR) technologies. VR, by definition, according to Steuer, is "a virtual system that consists of a computer capable of real-time animation, controlled through a group of equipment for simulating physical presence in places in the real world" [16]. Burdea and Coiffet (2003) also stated that VR could also engage its user's perception of sound, haptic, smell, and taste through computer interfaces that demonstrate real-time animation aside from the visual capabilities. Its attractive characteristics make it ideal for training applications in different fields, including

medicine, aviation, and the military. For instance, VR was used for surgery drills, combat training of soldiers, and flight exercising for pilots [17]–[19].

The succeeding sections of this paper comprehensively discuss the role of VR in construction safety achieved through a profound review of its applications, evolutions, and the challenges that it imposes with its utilization. It is in line with the objectives of conducting an in-depth study of VR to address the knowledge gap that introduces these advanced technologies, such as providing sensitive information regarding its general concept, beneficial applications, and possible limitations. Conveying the said information may also serve as guidelines for construction practitioners' consideration of implementing modern approaches to their regular safety procedures. Furthermore, this paper aims to present an inclusive evaluation of recent studies to discover new knowledge gaps to make way for more related and improved research topics.

2. Methodology

This section outlines a comprehensive analysis to discuss valuable observations into the existing construction safety literature and VR and identify future research's lack of knowledge. Keyword-based sources from electronic databases such as Scopus. The period studied ranges from 2010 to 2020, and the search was carried out using the "Title/Abstract/Keyword" field of the database, as mentioned earlier. The following keyword is "Virtual Reality" incorporated with another query search "construction safety," There where 69 documents identified through a database search, after removing duplicates, and by manually reading the abstract and parts of the entire articles considering the application of VR as a safety tool in construction safety, the number reduced to a total of 63 documents.

Using the Matlab text data analytics and applying a Latent Dirichlet Allocation (LDA), the abstracts were pre-processed. LDA is called a "topic model" since the defined word sets appear to represent the underlying topics that can be combined to describe each text in a corpus [20]. Topic modeling is a system used to model the search text as a mixture of subjects and each subject as a mixture of terms. The summary of the LDA topic results can be seen in Figure 1. The top four words in Topic 1 were as follows: environment, result, reality, training, application. This topic can be classified as training and application of Virtual Reality. Topic 2 comprised the following words: worker, hazard, construction, site, virtual. A topic can be classified as identifying hazards through visualization. For Topic 3 were: virtual, study, safety, construction. The subject can be classified as a study of virtual application in construction safety. Topic 4 with the following words: management, technology, safety, risk, research. It revealed there is potential research of VR technology in safety management.

Figure 1. Four (4) LDA topics generated through Matlab

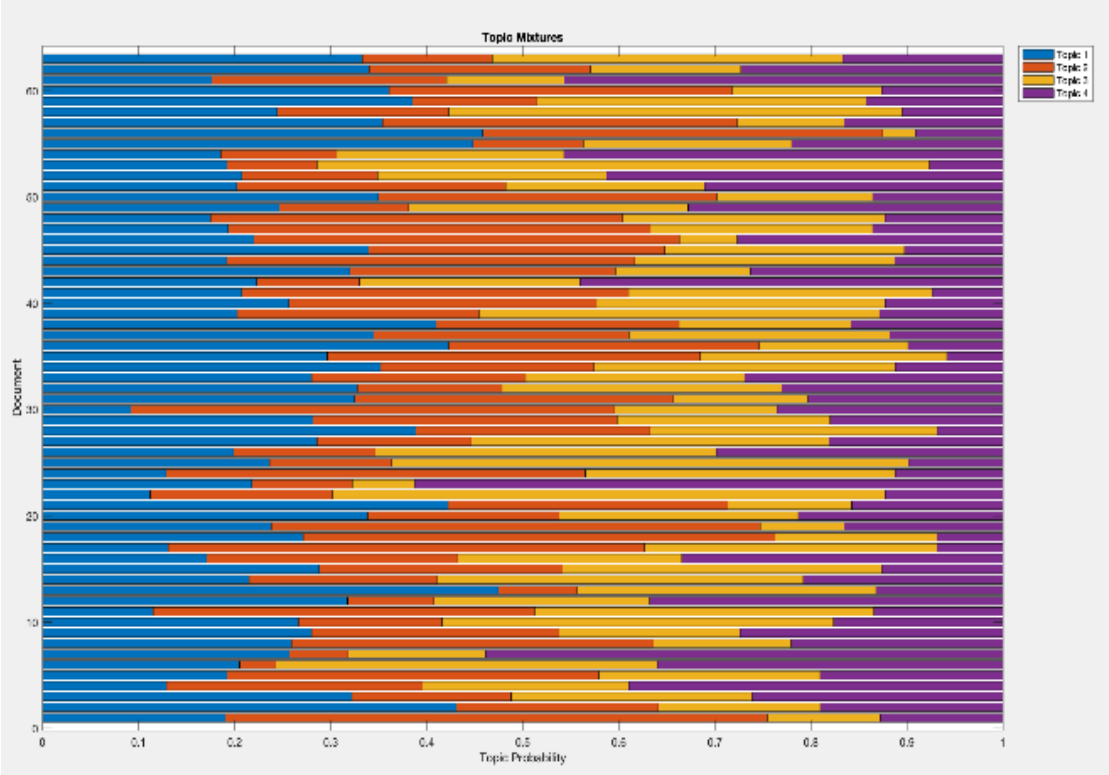

Figure 2. Topic mixtures generated through Matlab

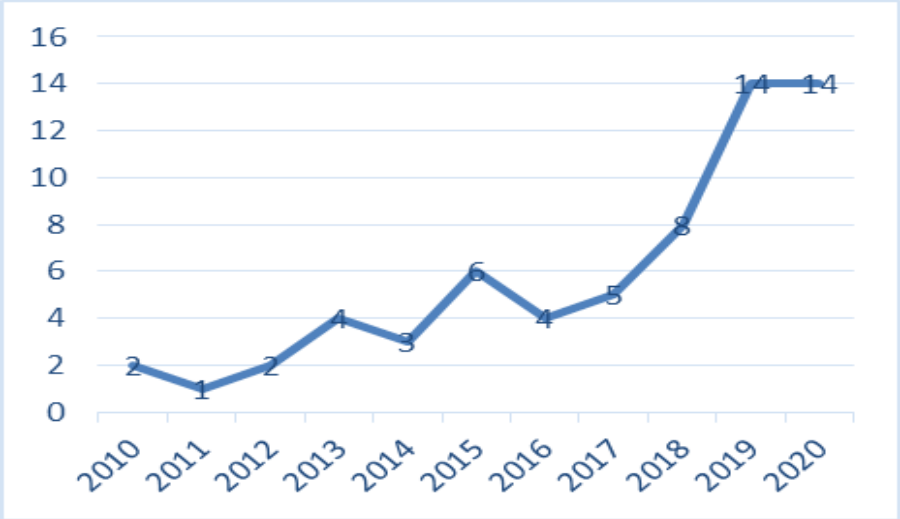

Figure 3. Number of papers published per year

As shown in Figure 2, the topic mixtures have been created using topics 1 to 4 with a different combination of topics that can be made. This graph is vital and used to create new topic VR-related topics and methods as a safety tool. Figure 3 shows the number of publications by year that suggested that the study of VR as a safety tool has improved.

3. Training and Application of Virtual Environment

Firming up safety training and management is one of the most operative measures to successfully diminish safety accidents in construction sites [20]. Today's generation has gradually embraced the idea of virtual reality (VR) environments as one of the multiple technologies available for educational intents. The academe and construction works have been tested to efficiently benefit from this immersion, especially in retaining construction safety knowledge [21]. As shown in Table 1, twelve (12) studies out of the 66 publications retrieved from 1997 to 2017 related to the VR applications in Construction Engineering Education and Training (CEET) have been systematically reviewed and categorized under Construction Safety and Training [22]. The said frequency makes it the second-largest application area of VR in CEET, also reflected in a literature review conducted by Zhou et al.

(2013). VR has been the most commonly applied advanced technology in promoting construction safety management [1].

According to Guo et al. (2012), VR offers several applications in the construction industry, including its innovative service as a 3-dimensional facility with interactive motions construction workforce's on-site safety management literacy [23]. With this, VR also effectively enables its users to take prudent precautions and proper approaches to different scenarios brought by the various hazards present in the construction site, as discussed by Wang, B. et al. (2014) [24]. The results of the study conducted by Jeelani et al. (2020) also recognized the efficiency of using an immersive training procedure for construction practitioners, stating that the said experience smoothed out the learning process for its users [25]. The said study also revealed that upon interviewing its participants, they acknowledged the "highly engaging and realistic experience" that they have undergone during the experimentation proper, which also instigated their responses during the training.

Several VR applications are materialized through research carried out. It is further elaborated on studies by categorizing as follows: preconstruction safety practices, safety training, education, hazard identification and assessment, situational awareness, and task compatibility [21]. Furthermore, these are the following specific VR applications, respectively:

1. Hadikusumo, 2002 and Rowlinson, 2004 explicitly developed a safety tool that adapted the knowledge of actual safety personnel for precautionary measures with the concept of VR as its backbone;

2. In 2011, Dickinson et al. then produced a "serious game," terminology used to distinguish the purposes of information and gaming technologies–either for entertainment or serious purposes (Sawyer and Rejeski, 2002. The serious game was used to educate construction trades students about trench and health safety. In fact, in a relevant study conducted by Pedro et al. (2016), it was reported that the use of VR-based training demonstrated a much stronger effect on students' "understanding, knowledge, and grasp of safety concepts" compared to that of the paper-based training";

3. A VR environment program integrating Building Information Modeling (BIM) with 2-dimensional images was designed by Chen et al. (2013) to enhance the trainees' ability to identify potential hazards brought by different energy sources. Zhao et al. (2009) established a VE simulation-based training program to raise awareness of the construction site's electrical risks. Zhao and Ye (2012) also studied electrical hazards in construction sites and developed a 3D Online-Game Based Training for safety improvement in construction [26]. These studies can further justify the claim stated in the study of Goulding et al. (2012) that VR indeed primes construction workers and staff to "unforeseen problems that may occur due to various kinds of mismanagement on-site"; and

4. Considering that construction projects differ in multiple ways and offer a wide range of hazardous possibilities, Li et al. (2012) altered an existing game engine to develop a multi-user virtual safety training program for tower crane dismantlement. It is further vindicated by Edirisinghe and Lingard's (2016) claim that "VR-based training demonstrated that it is a useful platform for tower crane operation (and iron laborer safety training)."

Realistic data gathered from real-life scenarios in construction sites were used by Mo et al. (2018) for their VR-based training experimentation, resting on the fact that using data-driven episodes is critical in the efficiency of using virtual reality for safety training [27]. Pena and Ragan (2017) also amassed construction accident reports provided by Occupational Health and Safety Administration (OSHA) and used these to develop a design of a virtual environment for construction and contextualize these through space, visuals, and texts [28]. In a study conducted by Cheng and Teizer (2013), it was also concluded that visualization technologies used in an ironworker training facility pose advantages which include enabling to record a replay of the implemented training, unbiased analysis of both safety and efficiency routine, an exhibition of the trainees' situational awareness, the study of the effectivity of trainee and trainer demonstrations in intricate and continuously changing construction procedures, and provision of a fascinating criticism from the training participants and trainees of future generations [29]. In 2018, Pham et al. developed an energy-efficient learning system (the interactive constructive safety education (eCSE)) using Web-based panoramic virtual photo reality technology for interactive construction safety education upon conducting a critical review of the literature and discovering the energy-consumption problems of conventional VR systems. Their study revealed that their developed eCSE system eliminates the limitations faced by traditional VR systems in terms of energy efficiency, adaptability with the trainee, more effortless execution, and improvement of learning usability [30].

Lucas et al. (2008) have also concisely pronounced the essential perks of the "cognitive learning" attained with the use of virtual reality training as compared to learning in the traditional methods performed in classrooms in the particular context of safety training for equipment operators [31]. This is also supported by a study on VR-based construction safety education system by Le et al. (2014), which stated that "collaborative VR has abundant potentials" in providing practical safety learning, as well as initiating joint efforts between trainees and improving

their quality [32]. Concerning this, Getuli et al. (2020) also supported this claim, stating that by observing the scenario of those under the immersive VR simulation of the construction site for safety training purposes, a positive collaborative climate is nurtured amongst the trainees their interactions [33]. Vahdatikhaki et al. (2019) also concluded that using VR on safety training (context-realistic training simulators) can significantly improve safety learnings and teamwork, as well [34]. Meanwhile, Golovina et al. (2019) have pointed out several factors that should be considered to ensure the effectiveness and functionality of using VR tools for education and training purposes. Some of these include the test group's size, impact on existing construction routines, and human behavioral issues [35].

4. Identifying Hazards through Virtual Application

A study conducted by Azhar (2016) revealed that or 4-dimension dynamic tools perform a better function in safety planning and management in construction sites when compared to that of the 2-dimensional static drawings, mainly because of its ability to give the user an immediate impression of the real circumstances that happen on-site [36]. Furthermore, he also came up with the general conclusions that VR technologies provide the following: 1) a preview of the hazard possibilities along the construction process, thus enabling complementing mitigation; 2) identification of the activity sequence and materials needed before beginning the construction works, and 3) a rational recreation on the activity sequence during the carrying out of investigations regarding occupational accidents on the job site. Furthermore, in a study by Lucena and Saffaro (2020), it was concluded that the combination of virtual reality technology with the investigation protocol for the virtual world makes the detection of hazards effective. Virtual reality technology has been proven valuable in providing construction trainees with "visual stimuli," making it easy to intuitively notice dangerous situations. An essential function of the protocol used was to induce the user to systematically focus on the potential hazards, especially with less obvious dangers found in construction or any job sites [37].

Still eyeing safety in the construction industry, VR application is limited to on-site hazard identification, awareness, and the likes. It is also used even to the extent of the site's people's psychological and social aspects. Enumerated below are some of the studies which engaged VR in exciting ways of analyzing construction safety practices:

1. Tixier et al. (2014) used a virtual environment in assessing the risk-taking behaviors of construction workers and staff, resting on the claim of various researches that it is one of the most significant factors in the majority of occupational accidents in the construction industry. The participants' emotional states were varied; then, they were exposed virtually to the hazards found on-site. Consequently, they measured perspectives on the risks that come with the dangers through questionnaires [38]. The same idea was proposed by Hasanzadeh et al. (2020), where the relationship of presence, mixed reality, and risk-taking behavior of the construction workers and the staff was analyzed using a VR environment (see Figure 1) [39];

2. An immersive VR environment was developed by Hasanzadeh et al. (2020) to explore the dormant effect of safety interventions (e.g., risk compensation). This study provides a preliminary understanding of how safety protections affect the risk-taking behavior of the subject, thus, giving ample ideas to the construction industry on how to wisely approach this issue towards the development of its safety practices [39];

3. VR was utilized by Habibnezhad et al. (2019) in their study regarding the factors that affect the postural stability of construction workers in the job site, especially when on elevated surfaces. It is rooted in the claim that falling from heights is one of the primary reasons for fatality and injuries at the construction site. The results of this study will be of significant contribution to the safety training of newly recruited workers to be subjected to heights [40];

4. Intending to test the effectiveness of VR technology utilization in safety training and simulations, Pinheiro et al. (2016) conducted a feasibility study of an eye-tracking technology that can analyze a construction worker's gazing patterns in his job site. The results will provide an understanding of how a worker perceives his environment and the presence of hazards [41]; and

5. A VR environment is used to evaluate the worker's field-of-view in alarm generation in a study conducted by Chan et al. (2020). According to their objectives, the proponents aim to provide "a fresh perspective to the growing adoption of wearable sensors by incorporating workers' awareness into the generation of hazard alarms." The study is presumed to lessen unnecessary alarm instigations, leading to better safety construction practices on-site [42].

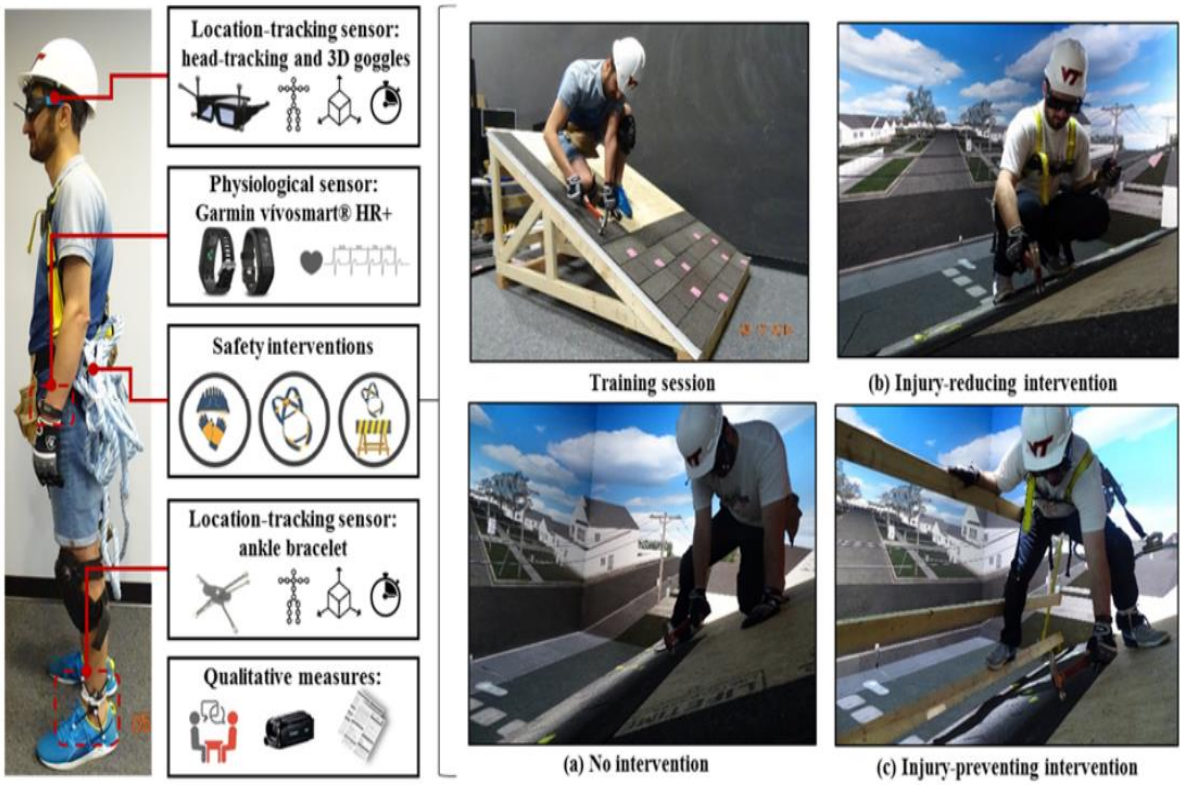

Figure 1. Experimental design by Hasanzadeh, S. et al. [39]

In addition to these, VR was also utilized to develop an attribute-based risk analysis method to identify latent hazards in building models performed by designers and construction procedural coordinators [43]. This kind of technology has immersed trainees in a real-time visualization to effectively expand their understanding of an actual construction environment and identify the hazards that come along it [29]. Park and Kim (2012) also reckoned that through virtual reality functions, a worker could deduce the exact risks present in their job site [44], including those under the construction and engineering practices. It was also revealed in a study, upon experimentation, that their subject groups were able to identify more hazards appropriately with the use of virtual reality as compared with the set-up where photographs and documents were utilized [45]. In 2014, it instigated a study that became one of the first trials in producing a comprehensive training procedure to develop workers' hazard recognition skills and is the first attempt to measure the "impact of a human-centric augmented virtuality tool on adult learning" [4].

5. A Study on Virtual Application in Construction Safety

The utilization of VR in the advancement of safety practices reaches the extent of health and safety managers' approval. It is used to review and possibly revise existing safety orders and form a "genuine health and safety work experience through virtual drills, instructions, and health and safety scenarios viable for construction health and safety training" [15], [46]. Shi et al. (2019) have also acknowledged the efficiency of using virtual reality in safety studies in a study they conducted regarding its performance as a tool for construction safety [47]. Table 2 summarizes the VR applications in construction safety in a 2015 state-of-the-art review conducted by Bhoir & Esmaeili. In the said table, the proponents, purpose, and benefits of utilizing VR as a tool in promoting on-site safety are located [21].

Similarly, Moore and Gheisari (2019) discussed their findings regarding VR-mixed reality systems' application objective for construction safety [48]. Four categories regarding the matter arose: hazard identification, hazard avoidance, hazard response and communication, and heavy equipment safety [48]. Some of the supporting researches under the following categories mentioned, respectively include:

1. Panoramic photographs and videos were utilized by Jeelani et al. (2017) to develop a virtual training environment to enable its users to engross themselves in the scenario and then correctly identify the potential hazards present;

2. Cheng and Teizer (2013) earlier designed a VR program that involved both real-time tracking and the virtual representations of the workforce and equipment, which served as an image of on-site scenarios and aided their refraining from perilous areas;

3. In 2018, Shi et al. engaged with my multi-user system installed with motion-tracking facilities to "enhance iron-workers interpersonal social interaction and communication simulating their work in high-rise buildings" (see Figure 2) [49]. A relevant study by Shafiq and Afzal (2020) concluded that the utilization of VR could "reduce the language barriers in communicating job-site safety to such a multilingual industry," which can advance the promotion of proper safety performances in the community [50]; and

4. Fang et al. (2014, 2017, 2018) united real-time tracking and BIM ideas to produce a VR environment to train and practice safety measures literacy of crane operators.

Figure 2. Views of the environment and motion capture system used in the experiment [49]

(from left to right: real-world set-up, VR first-person view, VR perspective view)

With the emergence of innovative technologies at present, acquiring research studies that reflect the applications of VR in improving the current status of construction safety has been straightforward. These research studies demonstrate VR's versatility and how it can be used in different ways to contribute to the on-site safety literacy and management of concerned individuals. For instance, Guo et al. (2012) developed a game-based interactive multi-client platform to serve as safety training for construction workers and staff. The said game presented a virtual environment–packed with real occupational hazards–where the trainees can experience a simulation that seems a lot like what truly happens to an actual site. The game also aims to empower the trainees' teamwork and communication while operating in the virtual environment [23]. Considering the accounted primary factors that instigate construction accidents, three core components were identified to form the conceptual framework that Guo et al. (2013) proposed to be followed when Virtual Prototyping: 1) modeling and simulation, 2) identification of unsafe factors, and 3) conduction of the safety training [51].

Concerning the construction safety awareness application of VR, a safety training and visualization system combines BIM, location tracking, augmented reality, and game technologies projected by Park and Kim (2013) [44]. Aside from offering an effective and vast safety practice and awareness knowledge using a mobile device, the system can also improve the laborers' real-time communication skills in a hazardous environment. Later in a 2015 study by Clevenger et al., it was reported after assessing the 3-dimensional visualization in safety training education in construction that the virtual construction safety training module integrated with BIM they established was "very effective for undergraduate students" [52]. In the same year, Sacks et al. made use of VR as a communication tool between designers and builders to "provide a forum for learning and proactive change of a design to make a project safer to build." The said study revealed that consultation and dialogues performed through virtual reality benefits designers' consideration of safety design in construction processes [53]. Côté and Beaulieu (2019) have also introduced a "VR Road and Construction Site Safety Conceptual Modeling Based on Hand Gestures," where an instinctual road plan VR application based on hand gestures was projected and established. The study demonstrated that the comfortable VR tooled applications they have developed presented a "natural, easy and fun to use" and can become a laid-back and user-friendly alternative for complex 3D engineering design software available (see Figure 3) [54].

Various VR applications were also enumerated by Zhou et al. (2013) in the literature review they conducted about the use of current innovative technologies in the improvement of on-site safety management [1]. VR was used in these, but are not limited to, the following applications:

1. Safety training in the process of steel erection (Irizarry and Abraham, 2005);

2. Permit the end-user in previewing a 3-dimensional project model for the preparation of design-for-safety-process (DFSP) and construction processes before actual construction is initiated (Rowlinson, 2000);

3. Identification of safety hazards during the design and construction phases, through assimilating VR construction model and DFSP database (Hadikusumo and Rowlinson, Rwamamara et al., Dawood et al., Zhang et al., 2002, 2010, 2012, 2012); and

4. Establishing a 3-dimensional scenery model for safety monitoring in a tunnel construction (Oiu and Wan, 2010).

Figure 3. Set-up showing the Leap Motion device affixed onto an HTC Vive VR headset (Left). Virtual hands (on-screen) positioned in VR in place of the real user's hands (Right) [54]

6. Potential Research of VR in Safety Management

Being oriented about the numerous contributions of technology on a primary concern such as construction safety will create more impact and appreciation on every scholar's part. Despite being hesitant in fully implementing technology as a medium for different constructional activities [11], [12], Zhou et al. (2013) managed to discover a 1986 paper in the database they utilized regarding the use of expert system technology in construction safety management [1]. Since then and particularly the years before 1991, little to no studies were published until 2008. Furthermore, supposing that "research topics were closely associated with technology application," it asserted that technology-related studies also evolved through time, aiming to meet the needs for that specific period [1]. Keenly considering all their gathered literature, they came up with a quick summary of sample technological applications on construction safety through time, and it goes as follows:

1. Before 1995, studies mainly focused on cause analysis, hazard identification, safety assessment, and safety information;
2. Significance of designers on construction safety was apprehended, therefore developing the Design for Construction Safety Toolbox, which merged design ideas to construction safety (Gambatese et al.);
3. In 2000, Rowlinson used VR and 3D modeling to develop a design-for-safety-process (DFSP) used to assess safety risks on-site;
4. A geographic information system (GIS)-based decision support system was established for safety supervision in geotechnical construction (Cheng et al.);
5. Safety monitoring was the underlying focus of research from 2011 to 2012, widely introducing global positioning systems (GPS), sensor-based technology, 4-dimensional visualization technologies, VR, etc.

Meanwhile, Park et al. (2016) claimed that the application of visualization technologies such as VR had been long implemented for enhanced learning purposes, particularly in the CEET field, ever since the early 2000s [55]. Handful researches on that period have paved the way for gradual VR advancement. It was then believed that the VR environment could enable its users to have a real-time and interactive execution of desired approaches in a particular setting, giving a better intuition than traditional 2-dimensional graphics. However, it was not until 2013 that the number of publications focusing on VR applications in CEET has increased (see Figure 1). Among that wave on VR-related publications are the studies conducted by Cheng and Teizer (2017) and Park and Kim (2013). A location tracking and data visualization technology as a medium for ironworkers' construction safety education and training and a framework for construction safety management and visualization system aimed to level up workers' knowledge about proper safety practices [29], [44].

Generally speaking, the studies on applying these visualization technologies were discovered to demonstrate positive effects in construction safety education and training, whether for the formal or informal environment [36]. Due to its rising status, the use of these innovations led to "a demand for a thorough review of the state-of-the-art of these developments" [56]. Some applications of VR in construction safety and risk management have encompassed a wide range of variety after several years since its emergence.

Observing and comparing all the gathered recent research studies presented in Table 1 to what has been previously discussed on VR's evolutions demonstrates that its application in construction safety management has come a long and broader way. Aside from the traditional focus of testing VR's capability of engaging workers to a better learning experience, most of these innovative studies have started integrating the field of psychology. Also, it comprises social aspects to develop a more profound and more complicated method for evaluating how construction safety is generally perceived. Recent VR evolutions not mentioned in the previous discussions are also noted, including the concept of V-REP. These vast steps of amplifying VR applications eventually offered new and significant information that will contribute to the industry's development, especially in terms of safety and risk management. With that, Table 1 reflects the researches' specific application on construction safety and the specified contributions and advantages of VR utilization in the study, respectively. Most of the contents of the said table directly came from ideas observed in the actual research paper.

Table 1. VR Application in Construction Safety, its Contribution, and Advantages

Citation	**Advantages**	**Application in Construction Safety**
[38]–[40], [42], [49], [57], [58]	Exposing the test subjects to the VR applied made their responsive behaviors realistic and more natural.	Understanding of workforce well-being and tendencies
	VR overcame the limitation brought by the difficulty of simulating hazardous scenarios that happen in real life.	
	It also allowed participants to experience unsafe situations without being exposed to actual risk.	
[59]	This study is highly influenced by improving the VR environment's "interactive conflicts visualization and dynamical construction safety simulation."	Hazard identification
[41], [50]	The utilization of VR technologies immersed participants in a real-time condition that produced almost entirely accurate responses in the experiment.	Identification of the workforce's limitation and preferences
		Identification workforce's
		Safety monitoring

Four particular applications of VR in construction safety were determined upon reviewing the literature. They are listed below and selected by perceiving the research's significance and results with a brief explanation.

Understanding of workforce well-being and tendencies. The majority of the ten types of research fell under this application. As previously discussed, VR technologies as a medium to integrate sociology and psychology into construction safety have attracted much attention from different researchers in recent years. These include attempts to study the construction workforce's behaviors to determine other platforms that may improve the current status of their on-site safety literacy. The research under this category focused on the workers themselves–specifically on how they usually act on and perceive the risks around them during work hours–to contribute ideas regarding the most effective safety training and education methods to be implemented. For instance, Hasanzadeh et al. (2020) stated that the findings of the research they conducted could have a significant impact on "how the construction industry approaches the development and implementation of safety interventions to offset the influence of risk compensation" [39]. Earlier, Habibnezhad et al. (2019) also asserted that their experiment results could be valuable to the training programs for rookie ironworkers to be laid open to extreme height and or steel erections. Meanwhile, these researches also share the same advantages of acquiring VR[40], as shown in Table 1.

Hazard identification. VR's influence was so high that it also uproots several innovative research ideas, including Shang and Shen's (2016) study [59]. A safety assessment model developed through a 4D BIM-enabled environment can be integrated into virtual environments for better experience and impact. Specifically, this model comprises three distinct features: 3D workspace representation, spatial-temporal conflicts detection, and 4D site safety analysis. These fall under hazard identification, a proactive procedure to mitigate the risks on-site during the actual work hours.

Identification of the workforce's limitations and preferences. VR technologies were also used to obtain actual recommendations from the construction workforce themselves. Considering Shafiq and Afzal's (2020) study,

surveys were conducted to identify factors that affect the workers' considerations in applying VR to their regular construction safety programs [51]. Immersing them in VR personally made them process the experience better and therefore come up with honest realizations. On the other hand, the experiment conducted by Pinheiro et al. (2016) also targeted to analyze the laborers' preferences on what to look either or overlook on-site through their visual patterns, which brings this discussion to the last application, which is safety monitoring [41].

Safety monitoring. The study of Pinheiro et al. utilized an eye-tracking technology that also tests VR's effectiveness on safety training and programs since VR is a direct application of the former. The in-depth analysis of workers' perception of the site, according to the proponents, "can determine the understanding level of safety requirements and guidelines adopted by a company or even indicate layout problems in the construction site planning." Through this type of study, the higher authorities can regularly keep an eye on what safety factors should need attention and apply proper actions to lessen their impact.

7. The Challenges of Virtual Reality (VR) in Construction Safety

Taking all applications and evolutions of VR in construction safety into account, it is fair to infer that VR's utilization can significantly improve the current safety platforms that construction companies immerse their workforce. According to Azhar (2016), the VR environment can offer relevant information that professionals (i.e., designers, engineers, and contractors) can apply to implement more effective procedures to mitigate or even eradicate inevitable construction hazards and risks [36]. Lin et al. (2011) also stated that scholars have confidence in VR's capability as a tool to address the difficulties that the construction industry faces regarding their campaign on proper safety practices [60]. However, being a relatively new instrument, VR application in construction safety still raises many challenges despite its numerous impressive uses. Garbaya and Zaldivar-Colado (2017) also noted that developing VR environments can generally be demanding "due to the complexity and limitations associated with these" [61].

Bhoir and Esmaeili (2015) indicated in a study that contrary to what most researchers claim on VR's advantages, practitioners' preference remains committed to hands-on safety training rather than VR-based [21]. Their research revealed that only 7% of their respondents–the majority of which are safety training professionals with an average of 13 years of experience–might opt to apply VR environment-based platforms on their safety training. None of these respondents also use VR environments in their safety training and methods. Besides, Hatem et al. (2018) suggested that older employees, which do safety practices inclined to the traditional techniques, hinder the industry's open-mindedness applying technological advents in their regular training [62]. It was also disclosed that "high set-up, implementation, and maintenance costs" are also considered barriers in adapting visualization technologies to improve safety on-site and the unfamiliarity on the return that investment on VR technologies can produce [38]. It is also in line with the study's findings by Azhar (2017). Accordingly, it pointed out that utilizing these tools requires an additional budget from the industry for its development and implementation. He then added safety and health personnel's inadequate knowledge about these tools and technical matters (i.e., "non-availability of safety elements and equipment" in the VR software database) as identified challenges in using VR. This claim is also supported by the study's findings by Bhoir and Esmaeili (2015), where it was revealed that "construction workers usually lack specialized computer knowledge." Their paper also indicated that skills needed for enhancing VR applications are seldom found, even among the engineering community. Aside from these, the optical risk is also raised as a barrier in thoroughly applying VR in construction safety since, as Clarke et al. (2016), stated long exposure and immersion in VR environments could cause dizziness [63].

Focusing more on the scope of the reviewing in this paper, presented below are the experimental research and the specific challenge imposed by their VR application in the study. The content of the challenges may or may not be directly derived from the paper itself but is conveyed through objective interpretations.

Table 2. Challenges imposed by Virtual Reality

Citation	Challenges
[38]	Partial control over the user's approach in moving in the VR environment
[49]	Inaccuracy between the user's actual movement and the virtual animation
[28], [45], [58]	Inaccuracy between real-time and virtual animation
[42], [59]	May offer limited scope overlooking other relevant factors
[35], [39], [42], [53], [64]–[66]	Work-intensive: "High set-up, implementation, and maintenance costs" (Shafiq & Afzal, 2020)
[57]	Subjective measuring tool
[40]	"Lack of peripheral visual inputs while wearing glasses." (Streepey et al., 2007)

[50]	Unawareness of the return on investment for VR utilization and its concept (Shafiq & Afzal, 2020)
[29], [41]	Technical complexity

VR has been revealed to be the most frequently applied advanced technology in terms of construction safety and risk management [1]. Since its emergence during the early 2000s [55], it has evolved to different kinds that meet various purposes under other circumstances (i.e., SAVES, Multi-user VR, CAVE, VDC tools, V-REP, etc.). In the previous section of this paper, loads of studies focusing on VR's feasibility as a tool to further understand and evaluate on-site safety are enumerated. Wang et al. (2018) also pointed out VR's provision of an "engaging and immersive environment" made it an ideal medium for site safety-related experiments [22]. It was also demonstrated that the significant advantage of VR utilization is its capability to surmount the limitation brought by the difficulty of simulating hazardous scenarios. It happens in real life by enabling its users to "experience" unsafe procedures without being exposed to actual risk.

Some of the general applications of VR that are mutually found between researchers ever since the growth of its number gradually increased are 1) hazard identification, 2) hazard avoidance, 3) hazard response and communication, and 4) heavy equipment safety [48]. However, recent studies have also integrated VR environments to more complex fields like psychology and social influence. As shown in this paper, VR's application has also now encompassed the 1) understanding of workforce well-being and tendencies, and 2) identifying its limitations and preferences. These studies revealed significant findings, which intimately involved principles from the very core of progression on-site–its workforce, that can produce ideal measures and amendments to enhance the status quo of construction safety and risk management. Nonetheless, just like any technological advancement, VR application still poses several challenges that are yet to be unraveled. Some of these, as discussed above, include the following challenges cited by more than one study: 1) inaccuracy between the user's actual movement and the virtual animation; 2) offering of limited scope, therefore, overlooking other relevant factors; 3) work-intensiveness, relatively high cost and maintenance; and 4) technical complexity.

8. Conclusion

Visualization technologies, particularly virtual reality, have progressed with time. As VR emerged into different types, it also entered a broader range of applications that paved the way for a more complex assessment of the current construction safety training platforms. Gathering the related literature on the role of VR in on-site safety management has offered a handful of information about its applications, evolutions, and challenges that can be generalized to develop an improved way of conveying the proper drills measures to the construction workforce.

Several gaps have been examined to further research endeavors on contributing to construction safety practices. First, it was observed that most researchers did not consider the financial background of utilizing VR, which is a relatively new tool, still unaccustomed. As an industry, construction companies must acknowledge the monetary aspect of implementing new programs [1]; therefore, it is appropriate to discuss this aspect to up the chances of this research to be considered. Second, it was also discerned that many of the researchers claimed that the study they have undertaken would help identify improvement points in on-site safety training. The researchers' focus is more on determining the appropriate technologies to amend a particular scenario [1], [67]. Not much about discussing a specific idea of applying the findings on real-time construction safety programs were noted. Some of the studies [38], [39], [41], [49], [68] also did not use actual construction workers for their experiment proper. Therefore, research that intimately inclines to a realistic construction set-up achieved through VR and involving people from the industry itself is crucial and will bear more accurate results. Lastly, while recent studies have focused on the workforce's behaviors, it is also equally important to give attention to the higher practitioners' dispositions (i.e., engineers and contractors) on the idea of VR as a construction safety training tool. As we all know, they are the ones who need elaborating convincing on the claim that this innovative medium is worth their time and budget. It is recommended that studies based on their perspectives on VR applications should also be considered for results. This way, other research opportunities intended to meet their expectations and standards may again emerge.

Acknowledgment

The Authors would like to express the most profound appreciation to PUP Engineering Science Department Family, namely; Juland A. Padilla, Kristel D. Lopez, Christian A. Mendoza and John Pual J. Pauya, without their support, the completion of this research would not have been possible.

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