ICCEPM 2020
The 8th International Conference on Construction Engineering and Project Management
Dec. 7-8, 2020, Hong Kong SAR

Construction Safety Training Methods and their Evaluation Approaches: A Systematic Literature Review

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Abstract: Due to hazardous working environments at complex, unstructured, and dynamic construction sites, workers frequently face potential safety and health risks throughout the construction process. In this regard, addressing safety challenges remains one of the top priorities. Construction workers' ability to identify and assess risks is acquired through training, which is one of the primary key factors to determine their safety and wellbeing in hazardous working environments. As such, safety managers constantly focus on the effectiveness of the training materials provided to the workers. However, the construction workers are considerably at greater risk of injuries and fatalities compared to the workers in other industries. In this regard, further studies are required to build up a body of knowledge on the conventional safety training approaches as well as their evaluation techniques in order to boost up the adoption by the practitioners in a widespread manner. This paper provides a systematic review of the current safety training approaches and the various techniques for measuring their effectiveness. The attributes of the current safety training methods for construction workers and their evaluation techniques are identified and analyzed. Results indicated that: 1) immersive environment-based training methods are effective than the traditional safety training methods; 2) this effectiveness can be empirically supported by evaluation strategies, but the current techniques are subjective, intrusive, and error-prone. This research offers fresh opportunities to investigate the training strategies by objectively monitoring the physiological responses of construction crews. The results of this study can be used by researchers and practitioners to identify and determine optimal safety training programs that could potentially become ubiquitous in the construction industry.

Keywords: construction, safety, training, evaluation, review

1. INTRODUCTION

The construction industry is one of the most labor-intensive industries, offering a large number of employment opportunities for millions of people worldwide [1]. Statistics show that construction workers are considered at greater risk of injuries and fatalities than the workers in other industries [2]. According to the US Bureau of Labor Statistics (BLS) [3], 1,008 workers lost their lives while working on construction sites in the US in 2018. Even though the construction sector constitutes about 5% of the workforce in the US, fatal injuries in the construction account for about 20.7% of occupational deaths across all industries [4]. As such, the construction workplace, with the complicated construction process, rapidly changing working locations, and dynamic resources, including staff, equipment, and materials, is regarded as one of the most unsafe industries. As a result, addressing safety challenges remains one of the top priorities in the construction industry.

Previous research suggests that most of the injuries occurring in construction worksites can be attributed to the inability of the workforce to predict, identify, and respond to hazards at the workplace [5]. More than 70% of construction injuries are associated with poor safety knowledge [6]. When workers underestimate the potential safety risk, they are more likely to indulge in risk-taking behavior [5]. As such, the ability to identify potentially hazardous conditions is an indispensable tool to mitigate risk, indulge in safe behavior, and achieve optimal construction environment. However, current studies show that workers, on average, are not able to identify more than 50% of safety hazards in a typical construction workplace [7]. Construction workers' ability to identify risks and their subjective analysis of the magnitude of those risks determine their attitude towards the potentially risky situation and their safety. To this end, safety training is an essential tool that raises workers' awareness of common risks associated with construction jobsite by augmenting the risk perception knowledge of the workforce. Also, the training encourages workers to make safety-conscious decisions, minimize risk, and avoid potential injuries. The variety of training schemes guarantees the attainment of a risk-sensitive attitude and ensures a safety climate in the workplace. In particular, the off-site instructional and on-site hands-on training programs allows for the systematic and methodological comprehension of safe behavior and proper practice in a construction jobsite. Researchers have highlighted that insufficient training is a significant reason that affects workers' hazard recognition performances and induces human errors [8–10]. If the workers do not have to possess the required schemata to be applied in potentially hazardous situations, they may be susceptible to injuries and fatalities. In order to enhance workers' perception of risk and hazards within the construction environment, as well as to reduce unsafe risk-taking behavior, workers are often put through safety training interventions. Through these training programs, the workers are trained to actively gather information necessary to identify conditions that are precursors to the potentially unsafe conditions.

However, despite the efforts to improve safety performance through safety training, the construction sector still accounts for disproportionate injury rates [11]. In this regard, measuring the effectiveness of assorted styles of safety training helps to create an effective training method. In particular, finding avant-garde ways to objectively and accurately measure the effectiveness of various aspects of construction training on the risk-taking behaviors of workers on the job site would allow for a more systematic avenue to tailor optimal construction safety training methods. Despite the potential importance of training and their evaluation strategies, few have been identified in the literature, and there is yet to be an organized effort to systematically investigate and analyze the current techniques. This paper, therefore, aims to contribute to the current body of knowledge by providing a systematic review of the available literature to identify and assess conventional safety training approaches, their evaluation strategies and suggest possible research directions. The results of this study can be used by practitioners to strategically identify the potentially ubiquitous safety training program to create an optimal construction environment.

2. RESEARCH METHODOLOGY

A systematic review was conducted to introduce and investigate the current methods of construction safety training as well as techniques to evaluate the effectiveness of the training. To achieve a target and structured review of the literature, the journals that deal with the subject were selected in two steps. In the first step, an exhaustive search was carried out on the following databases: ASCE Library, Scopus, Google Scholar, IEEE Xplore, Taylor, and Francis Online, Science Direct, and Web of Science. Several keywords such as "Construction," "Safety," "Training," "Virtual Reality," "Augmented Reality," "Visualization," "Hazard Behavior Analysis," "Risk Perception," and "Evaluation" were considered so that the search could cover a broad range of related disciplines. This round of search identified most related articles from several journals, including but not limited to Advanced Engineering Informatics, American Journal of Industrial Medicine, Applied Ergonomics, Automation in Construction, Construction Management and Economics, Ergonomics, International Journal of Engineering Education, International Journal of Environmental Research and Public Health, Journal of Information Technology in Construction, Journal of Computing in Civil Engineering, Journal of Construction Engineering and Management, Safety Science, Virtual Reality and Construction Safety, and IEEE Transaction on Biomedical Engineering, as well as conference proceedings, including ASC Annual International Conference Proceedings, and Construction Research Congress. Publications that did not comprise the keywords mentioned above in their titles or abstracts were screened out in the second step. In addition, irrelevant papers were filtered out after a brief visual examination of the content of the papers. Consequently, 45 of the most relevant papers within the scope of this study were selected for further analysis, as shown in Table 1. Figure 1 denotes the distribution of selected publications by years.

Table 1. Distribution of Articles by Findings

Findings of Research	Authors
Construction safety training methods	
• Traditional safety training methods	Lee et al., 2003 [12]; Williamsen., 2003 [13]; Halperin & McCann, 2004 [14]; Forck, 2005 [15]; Burke et al., 2006 [16]; Wallen & Mulloy., 2006 [17]; Choudhry & Fang., 2008 [5]; Cherrett et al., 2009 [18]; Dong et al., 2009 [19]; Li et al., 2012a [20]; Olson et al., 2016 [21]; Jeelani et al., 2017 [22]; R. Eiris Pereira et al., 2019 [23]
• Virtual reality-based safety training methods	Hadipriono & Barsoum, 2002 [24]; Hsiao et al., 2005 [25]; Wang Xiangy,2007 [26]; Ku & Mahabaleshwarkar, 2011 [27]; Dickinson et al., 2011 [28]; Guo et al., 2012 [29]; Li et al., 2012b [30]; Sacks et al., 2013 [31]; Kleiner, et al., 2014 [32]; Bhoir & Esmaeili, 2015 [2]; R Eiris Pereira et al., 2017 [33]; Lin et al., 2018 [34]; Gao et al., 2019 [35]; Jeelani et al., 2020 [36]
• 360-degree panorama-based safety training methods	Jeelani et al., 2017 [22]; Eiris et al., 2018 [37]; Pham et al., 2018 [38]; Pereira & Gheisari, 2019 [39]; R. Eiris Pereira et al., 2019 [23]; Eiris et al., 2020 [40]
Construction safety training evaluation techniques	Teo et al., 2005 [41]; Guo et al., 2012 [29]; Li et al., 2012b [30]; Ruttenberg, 2013 [42]; Kleiner, et al., 2014 [32] ; Jeelani et al., 2017 [22]; R. Eiris Pereira et al., 2017 [33]; Lin et al., 2018 [34]; Eiris et al., 2018 [37]; Pham et al., 2018 [38]
Potential of physiological monitoring for evaluation of safety training	Poh et al., 2010 [43]; Hwang, Seo, Jebelli, et al., 2016 [44]; Hwang, Seo, Ryu, et al., 2016 [45]; Wang., et al., 2017 [46]; Hwang & Lee, 2017 [47]; Jebelli et al., 2017 [48] ; Jebelli, Choi, et al., 2018 [49]; Jebelli,et al., 2018 [50]; Hwang et al., 2018 [51]; Jebelli et al., 2019 [52]; Choi et al. 2019 [53]; Habibnezhad et al., 2020 [54]

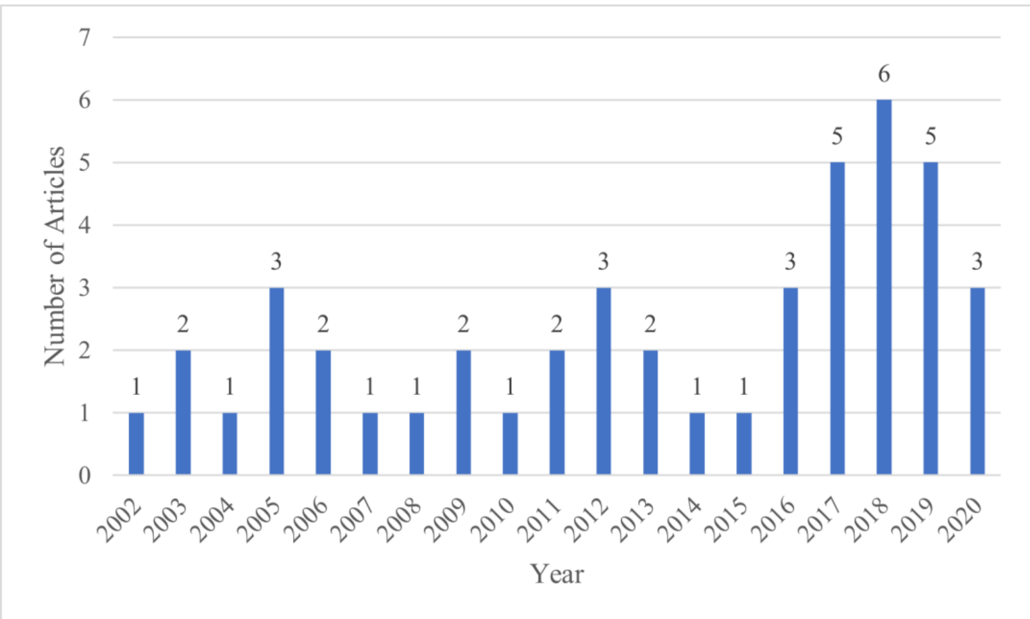

Figure 1. Publication distribution by years

3. RESULTS

3.1. Construction Safety Training

3.1.1.Traditional safety training methods

Safety training provides knowledge to the workforce to help reduce the injuries and fatal accidents on construction job sites [12,14,17,19,22,23]. Within current industry practices, safety training programs are offered to equip workers with detailed hazard information, safe behavior, and proper practices in a construction worksite. Much of the motivation for adopting these training efforts is to increase compliance with occupational safety and health rules and regulations [20]. Traditional safety training programs are usually lecture-based sessions that use multimedia contents, such as images, videos, slide presentations, or pamphlets [15]. As per the dynamic and hazardous nature of construction workplaces, safety training usually takes place in an off-site setting. In this regard, two-dimensional images and videos are employed to assist trainees in visualizing complicated construction scenarios. However, trainees cannot interact with images and videos and suffer from low levels of engagement due to the one-directional reception of material, which may translate to reduced learning by trainees [16]. To address this issue, interactive forms of training through discussions and toolbox talks have been employed to provide elevated hands-on learning [13,21]. However, the effectiveness of such hands-on training methods may vary given numerous influencing factors at construction sites, including the attitudes of the workers, the natural or trained cognitive abilities of the trainees, and the communication skills of the trainer and the trainees. Moreover, these methods cannot fully convey the dynamics found in real-world job sites [18]. These limitations innate in the current safety training approaches may be attributed to the inefficiency of the current methods to instill the complexity involved in a typical construction project.

3.1.2. Immersive environment-based safety training methods

Immersive environment-based training systems are very useful to train individuals in an environment that is risk-free and allows users to learn without real adverse consequences. Researchers have shown that training in an immersive environment would result in marked increase in technical skills, knowledge, as well as self-reported confidence and comfort [31,35]. In addition, retention of the experiential knowledge from training in a simulated immersive environment is pivotal in augmenting the hazard recognition and risk perception skills of the workers [26,31]. As such, safety training in the immersive digital environments has the potential to enhance training experience, eliminate or reduce health and safety risks, and in turn, induce safe behavior on construction job sites. In recent years, technological advancement has empowered researchers and practitioners to create immersive digital training environments mimicking the complexity of the real construction environment. These immersive environment-based safety training methods can be divided into two types: virtual reality-based safety training and 360-degree panorama-based safety training.

3.1.2.1. Virtual reality-based safety training methods

Virtual Reality (VR) technology can create immersive training environments that provide learners with experiential learning opportunities. These digital environments can visually replicate hazardous conditions that are impossible, dangerous, or expensive to experience in construction jobsites. This lifelike simulation has the potential to provide the workers with an immersive medium to visualize and interact with potential safety risks. In this context, researchers have devised a fair share of VR systems offering construction safety training. For instance, Albert et al. developed a high-fidelity virtual environment to immerse the workers in different working scenarios and assess their hazard recognition skills [32]. Hsiao et al. used Cave Automatic Virtual Environment (CAVE) system to simulate the scaffolding work and evaluated the impact of the platform height, platform width, and working groups in the risk perception of the participants [25]. Likewise, researchers have used interactive virtual environments for the safety training of the workers for scaffolding work [24,27] and tower crane operations [27].

Virtual reality enables trainees to explore the environment at their own pace and allows them to have control over their progress. Besides, optimizing the learners' experience during the learning process in a virtual environment can result in a paradigmatic shift in attentional allocation, engagement, and concurrently, knowledge retention [55,56]. In this regard, studies have often combined VR and gaming technology to create authentic, meaningful tasks and activities for construction education. As such, researchers have developed serious VR games to stimulate deeper learning, promote student interaction, and allow better situational awareness. For example, Dickinson et al. developed a serious VR game on trench safety education, which included fall, struck-by, and caught-in hazards [28]. Likewise, Lin et al. developed a 3D serious game allowing users to fill the role of safety inspectors, and in turn, evaluate their hazard identification skills [34]. While most VR-based training systems are single-user, several researchers have developed multiuser virtual environments that enable multiple people to collaborate in the same environment [29,30]. This approach enables users to understand the significant impact the decision making of an individual has on overall safety and wellbeing at a construction site. In addition, trainees can interact with other people to find out the best collaboration approach. In this vein, Guo et al. developed a highly collaborative VR safety training system that allowed several trainees to perform construction plant operations within a virtual environment [29]. Similarly, Li et al. developed a multiuser VR training program to allow trainees to learn and practice safe crane dismantling procedures [30].

In contrast to traditional safety training methods, VR-based safety training can be regarded as an effective approach to provide experiential safety knowledge in various hazardous situations without potential harm. However, several limitations have hindered the full adoption of VR technology as a standard method for providing safety training in the construction industry. Creating close-to-reality virtual settings of a dynamic construction environment to achieve a faithful representation of the actual world is time-consuming [33]. Moreover, the rendering required for the realistic representation of the scenes of congested construction settings entails high computational cost [2,31].

3.1.2.2. 360-degree panorama-based safety training methods

To address the limitations of time and computational cost related to developing an immersive virtual environment, the 360-degree panorama has been explored in the construction industry [39]. 360-degree panorama utilizes photography and videography to generate true-to-reality surrounding views of the construction environment. As such, the generated unbroken view of the surrounding creates a highly engaging and immersive experience due to the realism embedded in the photography and videography data. Since the 360-degree panorama utilizes digital imaging techniques, lower computational power is required to represent the jobsite. Thus, the low computational cost, ease of capture, and non-computer-generated simulation are the advantages of such a technique over the traditional VR-based safety system. Furthermore, the interactive exploration and visualization, and the capability of adding layers of information over the obtained data make the 360-degree panorama useful for hazard recognition in safety training [39]. In this regard, the 360-degree panorama has been used by researchers in the construction domain to improve the hazard identification and situational awareness of the workers. For example, Jeelani et al. used 360-degree panoramic images for simulating personalized accidents to train construction workers [22]. This study evaluated the sense of the presence of workers in a series of safety scenes. Likewise, Eris et al. captured a series of active job sites using the 360-degree panorama technique to develop a safety training environment [23]. This system allowed users to navigate throughout the construction site and evaluated the fall-hazard identification of the workers. Eris et al. conducted a similar study to evaluate the focus-four hazard identification capacity of the workers [37]. In another study, Pham et al. utilized a 360-degree panoramic technique to develop a learning system for enhancing safety education amongst the students [38]. The developed system allowed students to virtually visit a construction site to identify hazards in digital locations.

Although, 360-degree panorama offers an immersive experience due to the realism innate in the photography and videography data, several limitations regarding image quality, static vantage point and stitching parallax still exists [39]. Such limitations hinder the optimal implementation of 360-panorama based safety training method for practical application in construction jobsite.

3.2. Construction Safety Training Evaluation Techniques

Safety training is one of the most common interventions to improve hazard recognition and workplace safety. The evaluation of the workers' perception towards safety training programs, in terms of clarity, knowledge acquisition, relation to practice, and purpose achievement, is a key step in identifying the effectiveness of such programs. In this regard, questionnaires are shown to be an efficient way to analyze the workers' attitude and reception of the training program. Questionnaires can be structured to elicit perceptions of multiple aspects of safety training. Also, trends and patterns can be identified through questionnaires to uncover the limitations of the training program. In this context, Teo et al. used questionnaires to identify issues regarding safety training at active construction sites [41]. In another study, Lin et al. used a list of questionnaires to determine the effectiveness and suitability of the training programs [34]. Similarly, Guo et al. leveraged questionnaires to assess the performance of a designed VR-based safety training platform compared to the traditional approach [29]. Likewise, Li et al. evaluated the effectiveness of a multiuser VR training platform using questionnaires [30]. As such, the trainees participated in a survey concerning the training process after safety training sessions.

The ability to identify potential hazards is essential to indulge in safe behavior and achieve a safe construction environment. One of the important goals of safety training programs is to improve the hazard recognition skills of the workers, as unrecognized hazards can potentially result in undesirable workplace accidents and injuries. In this regard, the effectiveness of the training platform has been assessed by evaluating the hazard recognition performance of the trainees. In a study completed in May 2013, the behaviors of workers on-site were monitored before and after receiving OSHA 10-hr training. The evaluation suggested that OSHA 10-hr training significantly augment the hazard recognition performance of the workers [42]. In another study, Albert et al. evaluated the effectiveness of a high-fidelity virtual training environment by measuring its impact on workers' hazard recognition skills in different working scenarios [32]. Likewise, to evaluate the 360-degree panorama-based safety training method, Jeelani et al. compared the hazard recognition performance of the workers in pre-intervention and intervention phases [22]. The pre-intervention data provided an initial estimate and variability of workers' hazard-recognition ability prior to the intervention. The evaluation between the pre-intervention and intervention phases suggested that the intervention was effective in improving the hazard recognition performance of the workers.

Researchers have also combined both questionnaires and hazard recognition skills to assess the effectiveness of safety training platforms. For instance, to evaluate the usability and function of the 360-degree panorama-based training method for hazard identification and user satisfaction, researchers collected data from hazard identification test and post-test survey [23]. In the hazard identification test session, four different panoramic images, containing all the information trainees were expected to learn, were shown as interactive augmentations. In this session, trainees were required to actively explore the panoramic location to learn about the fall hazard. Following that, trainees were shown sequential panoramic images without any interactive augmentations and were required to identify all fall hazards. Data collected within the developed platform was used to evaluate the hazard recognition ability of the trainees. Besides, a post-test survey (i.e., questionnaire) was used to evaluate platform usability.

Although safety training evaluation has led to significant findings, construction practitioners and researchers have mainly relied on questionnaires and hazard recognition ability to assess the effectiveness of the training platforms. Such a subjective understanding of workers' attitude and ability is insufficient and prone to biases. In addition, these methods are unable to show changes in workers' perception of various safety risks overtime during the training. In this regard, the conventional methods of evaluating safety training approaches may not be efficient to comprehend workers' perception of safety risks, resulting in inadequate learning outcomes.

3.3. Potential of Physiological Monitoring for Evaluation of Safety Training

Given the deficiencies of safety training evaluation techniques, there is an increased need for objective and non-intrusive methods to continuously assess workers' perceived risk. To fill this gap, the continuous and quantitative assessment of 'trainees' perceived risk using physiological responses (e.g., cardiac activity, electrodermal activity, brainwave activity) acquired from wearable sensors (e.g., wristband, headset) can be an effective alternative to objectively evaluate the effectiveness of the safety training approaches. Physiological responses to an external stimulus can offer valuable information about an individual's health as well as the physical and mental state [47,50,54]. For instance, when an individual is in a highly stressful environment, the brain innervates the heart via the sympathetic nervous system. This change in the heartbeat (HB) mechanism results in variations in blood volume; these can be measured by using electrocardiography (ECG) and photoplethysmography (PPG) [44,45]. As such, the monitoring of workers' cardiac activity through noninvasive wearable sensors can help recognize the stress level of the workers throughout the training across different environments. In this case, it is important to monitor the workers in both the controlled training and the actual work environment to evaluate the risk perception of workers. Likewise, if the sympathetic branch of the autonomic nervous system is stimulated by external stressors, the number of active sweat glands increases, reflecting a higher Electrodermal activity (EDA) measurement [43]. In this vein, EDA can be a reliable metric to understand the perceived risk because perceived risk stimulates the sympathetic nervous system [53]. As such, noninvasive monitoring of EDA can give an objective understanding of the risk perception of workers performing training across different environments. Similarly, Electroencephalogram (EEG) has been widely used to record the changes in brain activity from diverse mental status (i.e., attention, emotion, cognitive load, etc.) [48,50–52]. The evaluation of the reflection of various stressors on brain activity is a reliable way to assess the risk perception ability of the workers [46,51]. In this regard, monitoring of the brain activity through noninvasive wearable EEG can provide an objective understanding of the perceived risk of the workers throughout their training in various environments.

4. RECOMMENDATIONS

Through the conducted literature review, various safety training approaches in the construction sector were identified. Lecture-based sessions and toolbox talks can be regarded as traditional training methods that are carried out in off-site and on-site settings, respectively. Immersive environment-based safety training methods are alternative approaches incorporated into the construction safety education to address shortcomings of traditional methods, such as the limited hands-on experience. However, currently, there is a lack of immersive training platforms in practice due to technical barriers. Future research is required to develop a more intuitive and seamless immersive experience, particularly for hazardous construction operations.

Moreover, prevalent safety training evaluation techniques were recognized in this literature review. Referring to the limitations of such techniques, the need for an alternative approach was indicated in this study. Thus, the potential of physiological monitoring of construction workers for assessing their perceived risk was introduced and highlighted. It is recommended that future research focus on the integration of physiological monitoring of workers and safety training as a means of providing reliable evaluative safety training platforms. In this regard, employing immersive virtual training platforms with a higher level of engagement is suggested. By investigating different physiological responses and acquiring appropriate metrics, further insights regarding the potential application of physiological monitoring for training evaluation can be achieved.

5. CONCLUSION

This study synthesized the current body of knowledge on methods of construction safety training and techniques for measuring the effectiveness of safety training. The paper identified and analyzed various safety training approaches aiming at enhancing workers' risk perception and hazard recognition ability. The review found that immersive environment-based safety training has a considerable advantage over the traditional method of safety training. Similarly, the review also presented the attributes of the conventional evaluation techniques of safety training. In this regard, it was found that current methods of evaluation are noncontinuous, intrusive, and prone to bias. The paper offers an alternative method of objective evaluation of the effectiveness of safety training programs through noninvasive, continuous physiological monitoring of the trainees during the training. Considering the feasibility of the physiological responses to evaluate the workers' risk perception, future research is required to assess the ability of physiological monitoring in immersive environment-based safety training approaches. The findings of this research can create avenues to develop promising training strategies by objectively evaluating them to determine the most effective approach for widespread implementation in the construction industry. Such an effective training method will augment the workers' risk perception and hazard recognition ability and will eventually allow the construction job sites around the world to operate at a safer capacity.

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