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Advancing Construction Safety Through a Combination of Immersive Technologies and Physiological Monitoring – A Systematic Review.

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Abstract: Physiological devices and immersive technologies are crucial innovations being implemented for construction safety. Physiological devices provide insights into the wellbeing of workers while immersive technologies have a potential to simulate or enhance construction environments. These two technologies present numerous benefits for construction safety and have been extensively implemented in various dimensions. In addition to the individual benefits of these two technologies, combining them presents more opportunities for construction safety research and numerous studies have been conducted using this approach. However, despite promising results achieved by studies which have used this technological combination, no review has been conducted to summarize the findings of these studies. This review therefore summarizes studies that have combined immersive technologies with physiological monitoring for construction safety. A systematic approach is employed, and 24 articles are reviewed. This review highlights four safety aspects which have been explored using a combination of immersive technologies and physiological monitoring. These aspects are (1) Safety training and evaluation (2) Hazard identification (3) Attention assessment and (4) Cognitive strain assessment. In addition, there are three main directions for future research. (1) Future studies should explore other types of immersive technologies such as immersive audio (2) Physiological reactions to hazard exposure should be studied and (3) More multi-physiological approaches should be adopted.

Keywords: Immersive technologies, Physiological monitoring, Construction safety

1. INTRODUCTION

Advancements in computer systems have led to the development of modern and innovative technologies. Among which include autonomous robots, Internet of Things (IOT), immersive technologies, and wearable devices [1]. These technologies hold great potential to improve workplace performance, making their integration into various industries increasingly significant [2]. In the construction industry, a lot of these technologies have been implemented in various dimensions, with safety being a major aspect. Numerous technologies have been explored for construction safety and notable among them are wearable devices and immersive technologies.

The invention of wearable devices has provided more opportunities for construction safety improvement. Wearable devices being used for construction safety come in two categories: (1) location sensors and (2) kinematic and physiological devices [3]. While location sensors track individual movements, kinematic and physiological devices measure changes in vital human parameters such as heart rate and brain activity [3]. Both categories have been utilized for construction safety. However, this study focuses on physiological devices due to their extensive adoption for more personalized construction safety research as evident in numerous studies [4,5,6]. Also, physiological devices are the category of wearable devices predominantly combined with immersive technologies for more advanced safety research.

Similar to physiological devices, immersive technologies have also been extensively implemented for construction safety. Immersive technologies are digital systems which allow users to have full engagement with simulated environments [7]. The most common types of immersive technologies are virtual reality (VR) and augmented reality (AR) [8]. While VR presents an opportunity for users to experience virtual simulations of the real world, AR enhances real environments by incorporating some digital elements [9]. Owing to the capability of VR and AR to simulate and enhance construction environments respectively, they have been widely adopted for various construction safety activities [10]. Immersive technologies, just like physiological devices, present numerous opportunities for construction safety improvement. However, a combination of these technologies provides more avenues for research.

Several studies have combined immersive technologies with physiological monitoring and promising results have been achieved. Different aspects of construction safety such as hazard identification [11,12], evaluation of safety training [13], and assessment of worker attention [14] have been explored with this combination. However, despite numerous studies using this approach, no review has been conducted to summarize these studies. Review studies have been conducted on the adoption of physiological monitoring for construction safety [3,15]. Similarly, review studies on the application of immersive technologies for construction safety have been undertaken [2, 16]. However, no attention has been given to the integration of these technologies. To bridge this gap, this study summarizes existing evidence on the combination of immersive technologies and physiological monitoring for construction safety advancement. The review seeks to achieve the following objectives: (1) Present an overview of construction safety aspects being explored using a combination of physiological monitoring and immersive technologies. (2) examine gaps in studies and suggest directions for future research.

2. RESEARCH METHODOLOGY

This review follows a systematic approach. Articles were extracted from three databases: Scopus, Web of Science, and PubMed. To ensure that only articles relevant to the study were identified, three sets of keywords were employed for the database search. After the database search, articles were evaluated to ensure they met the inclusion criteria. Table 1 shows the keywords used for database search.

Table 1. Keywords for database search

Keywords (January 02, 2024)
"Virtual reality" OR "augmented reality" OR "VR" OR "mixed reality" OR "immersive virtual environment" OR “immersive environment” OR “immersive audio”
"heart rate variability" OR "Heart rate" OR "thermoregulation" OR "electrocardiogram" OR "skin temperature" OR "respiration rate" OR "electromyography" OR "muscle activity" OR "physiological measures" OR "physiological monitoring" OR "eye tracking" OR "electroencephalograph" OR "electroencephalography" OR "eog" OR "EEG" OR "brain sensing"
“construction sites” OR “civil engineering” OR "Construction worker" OR "construction industry" OR "construction trade" OR "construction sector" OR "construction" OR "industrial construction"

The inclusion criteria for studies in this review were as follows: (i) Journal or conference papers published in English; (ii) articles with experimental or observational studies; (iii) studies that used immersive technology; (iv) studies that used at least one physiological metric; and (v) studies assessing construction safety. To ensure that the selected studies met the set criteria, a three-step screening process was conducted. In the first step, the search output was refined on the databases using the filter function to include only journal and conference articles written in English. A total of 276 articles were found, and after filtering, 239 articles were retrieved and exported. Fifty-eight (58) of these studies were identified as duplicates and eliminated, leaving 181 articles for further assessment. In the second stage, titles and abstracts were examined. A total of 147 unrelated studies were eliminated, leaving 34 studies. The final step involved a full-body assessment. Ten (10) studies were excluded after full-body evaluation, and a total of 24 studies were included in this review. Once studies to be included in the review were determined, relevant data and insights were extracted from the articles. The extracted details focused on the dimensions of construction safety evaluated by the studies, the physiological metrics used, and the immersive technologies employed. Figure 1 shows the systematic process of article selection.

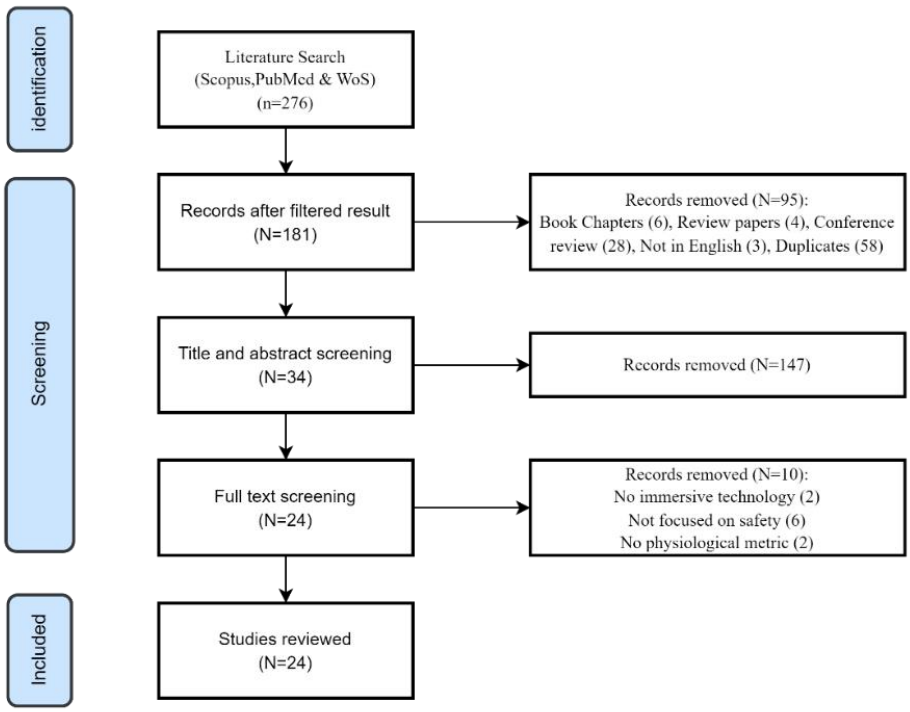

Figure 1. Systematic process of article selection

3.0 FINDINGS

3.1 Characteristics of included studies

Table 2 presents some characteristics of the various studies included in this review. This includes the immersive technology employed, physiological metric utilized, and the construction safety dimension evaluated. Twenty studies utilized virtual reality while three (3) studies utilized augmented reality. One (1) study employed a combination of virtual and augmented reality. Four categories of physiological metrics were utilized. Twelve (12) studies employed brain metrics (EEG), nine (9) studies used ocular metrics, nine (9) studies also utilized cardiovascular parameters and four (4) studies explored various skin metrics which include electrodermal activity and skin temperature. All studies investigated certain aspects of construction safety and four categories were found. The subsequent sections will delve deeper into each safety aspect.

Table 2. Characteristics of included studies

Reference	Immersive technology		Physiological metrics				Safety Dimension
	VR	AR	EEG	Ocular Metrics	Cardio-vascular	Skin Metrics	
[13] Choi et al. (2023)	✓		✓	✓			Safety training and training evaluation
[17] Someya et al (2023)	✓				✓		
[18] Song et al (2022)	✓		✓				
[19] Comu et al. (2021)	✓			✓			
[20] Huang et al. (2020)	✓		✓		✓		
[21] Sakib et al (2020)	✓				✓	✓	
[22] Lee et al (2022)		✓	✓	✓	✓		
[23] Xu et al (2019)	✓				✓		
[24,12, 25,11] Jeon & Cai (2023,2022, 2022b; 2021)	✓		✓				Hazard Identification
[14] Noghabaei et al. (2021)	✓		✓	✓			
[26] Hamasaki et al (2020)	✓						
[27,28] Albeaino et al (2023a, 2023b)	✓			✓	✓	✓	Attention Assessment
[29,10,30] Kim et al (2023,2021a, 2021b)	✓			✓			
[31] Pooladvand & Hasanzadeh (2023)	✓				✓	✓	
[32,33] Qin & Bulbul (2023a, 2023b),		✓	✓				Cognitive Strain assessment
[34] Tehrani et al. (2021)			✓				
[35] Habibnezhad et al (2019)	✓	✓			✓		

3.2 Dimensions of construction safety being assessed

3.2.1 Safety training and training evaluation

Immersive technologies such as virtual and augmented reality are being used to enhance traditional safety training. However, assessing training efficiency, which is crucial after using these methods predominantly relies on subjective methods. To achieve more accurate and reliable assessments, researchers are now incorporating physiological monitoring into immersive-based training to objectively assess training efficiency and learning performance. Some studies in this review [13, 20] incorporated physiological monitoring into VR-based safety training and developed models to predict training efficiency. Also, by integrating eye tracking metrics into VR based training, Comu et al. [19] assessed factors which influence safety training performance and found that individual factors such as professional and academic background have an impact on training performance. Findings from these studies serve as a foundation for more personalized and efficient safety training procedures.

3.2.2 Hazard identification and prediction

Construction sites possess numerous hazards which necessitates efficient hazard identification to keep workers safe. Current hazard identification methods are manual, making them inefficient due to the complex nature of construction sites. However, some studies in this review reveal a more efficient and objective approach for identifying hazards. Jeon and Cai [11] developed a hazard prediction model using brain signals (EEG) of individuals who were exposed to hazards in virtual construction environments. The model achieved an accuracy of 95% in predicting two classes (presence or absence of hazards). To test the feasibility of predicting distinct categories of hazards using such an approach, the authors conducted a follow-up study [12], where they developed a multiclass hazard prediction model that yielded a prediction accuracy of 82%. Also, Noghabaei et al [14] developed a hazard prediction model using EEG and eye-tracking metrics. The model achieved an accuracy of 93%. The results of these studies highlight the potential of developing hazard prediction models using a combination of virtual reality and physiological monitoring. The studies also provide evidence on the capability of physiological metrics to react to varying hazard conditions.

3.2.3 Attention assessment

Maintaining high attention levels during construction activities is crucial to prevent accidents. A combination of physiological monitoring and immersive technologies presents an efficient method for assessing attention levels, as well as a technique for identifying factors that influence worker attention in varying construction conditions. By creating a virtual construction environment and incorporating a simulated drone presence, Albeaino et al. [27, 28] examined the impact of drones on the attention levels of construction workers. Also, Kim et al. [10, 30] by simulating a road construction project developed an attention prediction model with 72% accuracy using EEG and Electrodermal signals of participants. In addition to assessing worker attention levels, some studies have explored other dimensions, such as situational awareness. Pooladvand and Hasanzadeh [31] by conducting a virtual experiment found that high mental demand and time pressure reduces construction workers' situational awareness and attention to risk during hazardous task. These studies highlight efficient methods for assessing factors which influence attention levels of workers. By utilizing similar techniques, construction activities can be simulated, and workers' attention levels assessed. Also, factors which reduce worker attention can be assessed in virtual environments before actual construction commences. This will facilitate the implementation of proactive measures to avoid inattention during actual construction.

3.2.4 Cognitive strain assessment

Construction activities, due to their complex nature, require considerable mental effort. This often leads to adverse cognitive conditions, such as high mental workload and mental fatigue. These cognitive states often possess negative influence on the safety behaviors of workers and can increase the risk of accidents [36]. Therefore, assessing cognitive dimensions such as mental workload and attempting to keep them at optimal levels is crucial for safety performance. Physiological monitoring, coupled with immersive technologies, presents an opportunity to assess the cognitive demands of various construction activities and situations without exposing workers to actual site conditions. Tehrani et al. [34] assessed the effects of height on the mental fatigue of construction workers using virtual simulations and EEG. Their findings indicated that workers at height experience higher levels of mental fatigue. This study reveals an approach to assess the cognitive demands of various construction activities before actual construction. Some studies also sought to investigate the influence of immersive technology-based support on cognitive status. Qin and Bulbul [32, 33] examined the influence of augmented reality (AR) support on individuals' mental workload during a simple construction task. The outcomes of these studies suggest that integrating AR support into construction activities has the potential to reduce mental workload. However, more validatory studies should be conducted in this regard.

4.0 DISCUSSIONS AND FUTURE RESEARCH DIRECTIONS

This review summarizes studies that have combined immersive technologies with physiological monitoring for construction safety. Findings from the review highlight the effectiveness of this technological combination in addressing various aspects of construction safety. Some of these safety aspects include improving the efficiency of safety training, more objective hazard identification, attention assessment, and gaining insights into the cognitive demands of some construction activities. Although the studies in this review have addressed crucial construction safety issues, numerous gaps exist, and the potential of physiological monitoring and immersive technologies can be harnessed further.

Firstly, many studies have addressed hazard identification and hazard prediction. Although hazard identification is crucial, construction workers still undertake activities in hazardous environments. Therefore, it is important to understand how physiological metrics respond to hazards. Future studies could use virtual environments to explore physiological reactions to varying hazards. For example, a fall risk prediction model can be developed based on physiological reactions to virtual fall hazards. Such a study will serve as a foundation for the creation of personalized fall prevention systems. Secondly, the studies in this review utilized either virtual or augmented reality. Other immersive technologies, such as immersive audio exist. Immersive audio can be used to simulate more realistic construction sounds, making it a key technology for more accurate noise-related research. Future studies can therefore utilize a combination of immersive audio and physiological monitoring to assess the impacts construction noise has on workers. Thirdly, the reviewed studies utilized a maximum of two physiological metrics. In the context of hazard identification, studies employed either EEG or ocular metrics (eye tracking). It is crucial to explore other physiological metrics such as skin temperature, electrodermal activity and cardiovascular metrics. Furthermore, a multi-physiological approach may result in enhanced model accuracy as well as provide insights into the best physiological metrics for hazard prediction. Lastly, comparisons should be made between physiological reactions in virtual scenarios and physiological reactions in actual construction settings. Such a study will provide information on the extent to which virtual scenarios represent actual environments.

5.0 CONCLUSIONS

This paper provides a review of studies that have combined physiological monitoring with immersive technologies to enhance construction safety. The study utilizes a systematic approach and relevant articles were extracted from three databases: Scopus, Web of Science and PubMed. Following a three-step evaluation process, twenty-four (24) articles were selected for review. This review assessed various aspects of construction safety being improved through a combination of immersive technologies and physiological monitoring. These safety dimensions were found to be in four categories which are (i) Safety training and training evaluation, (ii) hazard identification and prediction, (iii) assessing worker attention, and (iv) assessment of cognitive strain which includes mental workload and mental fatigue. In addition to assessing various safety dimensions, the study also explored the types of immersive technologies and physiological metrics being used. In terms of immersive technologies, it is found that virtual reality (VR) and augmented reality (AR) are the most employed. For physiological metrics, four categories were found. These categories are brain metrics (electroencephalography), ocular metrics (eye tracking), cardiovascular metrics such as heart rate and skin metrics which include skin temperature and electrodermal activity (EDA). Numerous research gaps were identified, and future directions proposed. Firstly, future research should explore physiological responses to hazards as this could pave way for more personalized hazard prediction and prevention. Secondly, the potential of other immersive technologies such as immersive audios should be explored, particularly for noise related studies. Thirdly, future studies should adopt more multi-physiological approaches, especially for hazard prediction studies. Lastly, more comparisons between physiological reactions in virtual settings and physiological reactions in physical environments should be conducted.

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