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Harnessing Virtual Reality to Mitigate Heat-Related Injuries in Construction Projects

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Abstract: The construction industry has witnessed a surge in heat-related accidents alongside rising summertime temperatures, exposing workers to potential injuries. The absence of specific heat stress standards by the Occupational Safety and Health Administration (OSHA) underscores the urgent need for more comprehensive and interactive educational materials to prevent such incidents in construction projects. This study proposes the adoption of an interactive Virtual Reality (VR) application to offer construction workers realistic and effective training, mitigating heat-related injuries. During the training sessions, VR headsets were utilized to immerse workers in two lifelike scenarios: (1) Addressing self-care during heat exhaustion; (2) Assisting a coworker experiencing heat exhaustion. A case study evaluated the effectiveness of the proposed VR training for 82 construction workers from two companies. Company A had traditional training, while Company B used VR training. Both groups took pre- and post-assessment surveys with six questions. The pre-assessment found no significant knowledge difference between the groups. After training, VR showed a significant reduction in incorrect answers compared to traditional training. Statistical tests confirmed the superiority of VR training (p-value = 0.00152 < 0.05), suggesting its effectiveness in preventing heat-related injuries in construction compared to traditional training methods.

Keywords: heat-related accidents; construction safety; virtual reality

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1. Introduction

Construction employees face a high risk of death, injury, sickness, and decreased efficiency due to their heat exposure while working. Due to heat-related issues, 285 construction workers died from 1992 to 2016, accounting for over a third of all occupational fatalities in the US [1]. The actual number of heat-related deaths may be higher due to incorrect categorization. The upward trend in heat-related deaths has been on the rise, coinciding with a hike in normal summer temperatures over the same time frame. According to Dong et al. (2019), nearly three-quarters of heat-related deaths happened during the months of summer (June, July, and August) [1].

Additionally, heat-related illnesses (HRIs) that do not result in death are more prevalent; however, they may go unrecorded in surveillance information since they often go unnoticed. According to Arbury et al. (2014), individuals seeking medical care aged from 19 to 45 had job-related HRIs as a more common reason for emergency room visits than any other type of job-related injury, as stated in the state of North Carolina's data from year 2008 till year 2010 [2]. Hesketh et al. (2020) revealed that an analysis of workers' compensation data collected from the state of Washington between the year 2006 and the year 2017 indicated that the construction sector had the highest number of accepted claims for HRIs during the warmer summer months and the third quarter [3]. Construction employees working at locations with high temperatures were susceptible to injury due to impaired cognitive function, sweaty and slippery hands, dizziness, cramping and muscle strain, slowed reaction time, and vision obstructions that were caused by fogged-up eyewear [4]. Washington State research on heat-related damages among construction employees who work outdoors showed that with each one-degree Celsius rise in maximum daily humidex (a metric that reflects the perceived heat resulting from the mixture of humidity and temperature), the likelihood of enduring a traumatic injury rose by 0.5% [4]. According to NIOSH (2016), certain factors such as inadequate heat adaptation, low fluid consumption, prior history of HRIs, pre-existing health conditions, age, pregnancy, and use of certain prescription or non-prescription medications may heighten the susceptibility of certain construction workers to HRIs [5]. According to Quandt et al. (2013), workers who resided in homes without cooling or with high humidity levels may also be more susceptible to HRIs as it decreases their capability to rejuvenate from heat exposure during the day [6]. Conditioned ventilation, isolation of hot operations, protective coverings, prevention of leaks of steam and other moisture causes, obstacles, and fans are examples of engineering controls that can be used in order to control the heat in construction locations. However, sometimes they are not viable to implement in the construction locations. Currently, OSHA lacks a dedicated standard for addressing heat stress in the workplace. This gap leaves workers vulnerable to heat-related health risks, especially in industries with high heat exposure, such as construction. Developing a comprehensive standard would provide essential guidelines and preventive measures to ensure worker safety and well-being in extreme heat conditions.

2. Literature Review

In recent years, scientists have employed virtual reality (VR) and mixed reality (MR) methods for various safety implementations, including training, monitoring risks, and preparing for construction. To identify the gap in the body of knowledge, Google Scholar has been used to conduct a review of the literature using the following keywords in different combinations: (1) Virtual Reality, (2) Construction Safety, (3) Training, (4) Heat Stress, (5) Heatstroke. The results of the literature review are summarized below:

A study addressed the lack of traditional construction safety education in China by incorporating a VR training system into safety education. The training system of VR construction safety permits numerous users to be present simultaneously while completing simulations of construction accident safety hazards. The training system includes a virtual reality and vibration system. The VR system primarily uses 3Dmax for 3D modeling and Unity for animation and interaction design. The vibration system is added to improve the user's experience by providing a sense of vibration through the use of six low-frequency vibrating horns [7]. A VR module was created and developed by Rokooei et al. for safety training in the roofing industry. The VR application was totally created and built utilizing an agile methodology and an industry-based expert flow. The results were analyzed using a quantitative method, and many facets of the VR module were looked into. The outcomes demonstrated that the VR module had a favorable influence on roofing experts' opinions on the viability of using VR as an additional training tool [8].

Another study examined the potential uses of VR in construction, particularly in enhancing safety in construction sites and education. The outcomes of creating and testing the prototype show that the immersive VR prototype has a noteworthy enhancement in the ability to recognize hazards when compared to conventional safety instruction. Moreover, the appraisal of its effectiveness and practicality implies the possibility of VR in enhancing construction education, opening up the possibility of VR being utilized as a teaching instrument to conventional education on a broader scale later on [9]. A study explores the benefits of using Augmented Reality (AR) and VR in construction management. It found that AR can be used in scheduling, monitoring, training, safety, and quality control, while VR can be used in visualization, training, safety, and quality control. AR and VR can also be used for remote communication. The research identified areas where AR and VR can be used effectively to save time and costs [10].

A researcher reviewed the effectiveness of traditional and computer-aided methods in improving safety in the construction field. Conventional methods had strong evidence of effectiveness, while computer-aided technologies showed potential but needed more research. These technologies have advantages in simulating real-world environments, providing text-free interfaces, and increasing user engagement. Acquiring knowledge, dangerous behavior modification, and average damage decrease were all used to assess efficacy [11]. Construction safety is a major concern for companies, and some have turned to Virtual and Augmented Reality (VR–AR) to improve employee protection. A study reviews current VR–AR technology and its use in construction safety, including training and evaluation methods. It classifies VR–AR features in terms of technology, safety procedures, and implementation areas. While VR–AR has the potential to improve construction safety, further research is needed. The study suggests potential areas for future research to address deficiencies in current VR–AR applications [12].

Another study examined the effectiveness of immersive virtual reality-based safety training (IVST) in the construction industry. It compares the performance of inexperienced and experienced workers in identifying hazardous scenarios and selecting personal protective equipment. The study found that the IVST system improved the safety performance of all participants, with novice workers showing a higher improvement in identifying hazardous situations. It suggests improvements for the current IVST program based on the impact of trainees' individual characteristics [13]. VR can be an effective way to train workers in safety procedures in the precast/prestressed concrete field. One study established a VR training module to give safety training in an economical and repeatable way, aiming to decrease typical plant injuries. The analyses of efficacy and effectiveness were done in order to assess the implementation of the VR module. Results revealed that VR training is more immersive and effective in helping individuals grasp safety procedures and gain a realistic understanding of a precast/prestressed concrete plant [14].

A lack of hands-on training is a major contributor to preventable accidents in construction. To mitigate this, Xu and Zheng developed a multiplayer VR training platform to offer repeatable, flexible training in a safe virtual environment. A survey of the people that used the training platform showed that workers were better trained and remembered critical information more effectively with VR technology, as it allowed them to experience hazardous situations without physical harm. The research concluded that adopting this VR platform could bring numerous benefits and enhance human–machine interaction research in construction training [15]. One researcher proposed a VR system for construction safety training that used electroencephalography (EEG) and physiological data for real-time assessment. The system included novel algorithms and had an accuracy of over 80%. A study with 117 construction workers showed that it could identify workers with health risks. The system played a crucial role in promoting safety awareness and physical well-being and reducing incidents [16].

One study addressed the effects of social influence in hazardous situations by using a Multi-user VR (MVR) system with motion tracking to simulate hazardous scenarios and examine the effect of social influence on workers' safety behaviors. The study involved 126 participants walking across a virtual plank between two tall buildings while observing different situations; for instance, someone walking slowly or falling. Results showed that social influence played a crucial role in determining participants' safety behaviors in the simulated dangerous environment [17]. A Virtual Reality program for bridge inspector training with drones was described by Li et al.. The system included a Unity-based bridge inspection simulation, a remote-control interface, real-time feedback, and a post-training evaluation. The pilot study proved that the program accurately identified training needs and improved inspector skills and confidence in working with drones. The system provided a platform for future advancements in human–drone cooperation in civil infrastructure inspections [18].

It has been demonstrated that VR can provide an experience that enhances the effectiveness of learning. Using VR with head-mounted displays was helpful in training crane operators, improving safety, and reducing costs. A study introduced VR training systems for three types of cranes (overhead, container, and tower) and tested their effectiveness through an experiment with 108 students. Results showed significant improvement in students' self-efficacy in crane operation. The improvement was found to be due to observed usefulness, usability, and feeling of presence, as revealed by double mediation analysis [19]. Another study explored the effect of VR training on workers' hazard recognition abilities and behavior. Through the use of structural equation modeling, 60 participants were studied. The results showed that VR system features played a significant role in knowledge acquisition, behavioral intention, and satisfaction. The study also found that higher levels of presence in VR training may not necessarily lead to stronger behavioral changes. These findings can assist in designing VR training programs that are cost-effective and make the most of VR technology for industries [20].

A researcher designed a VR training program that taught people how to learn techniques for surviving earthquakes in indoor settings. The training made use of commercial VR devices and populated virtual environments with furniture to simulate a realistic earthquake. The effectiveness of the approach was tested, and results showed that participants who underwent the training performed better than those trained by alternative methods in avoiding physical damage and detecting dangerous objects [21]. Çakiroğlu and Gökoğlu proposed a study using VR-based training to teach basic fire safety behaviors to primary school students. A virtual environment was designed, and students received training through it, with real-life reinforcement. The results showed that students' fire safety behaviors improved with VR training, and most could transfer their skills to real-life situations. The combination of VR modeling and in-situ training contributed to behavior improvement. The study provides suggestions for VR-based behavioral skills training practitioners and researchers [22].

The literature review indicates that there are currently no VR materials available for heat stress training, as confirmed by OSHA, the research sponsor. The goal of this research is to address this gap by developing immersive and effective VR training for heat stress. Realistic scenarios using VR would be created that teach workers to recognize signs of heat stress and adopt preventive measures. This research aims to enhance occupational safety by providing accessible and impactful training to a wide range of industries.

3. Methodology

This research methodology includes developing VR interactive applications to immerse the construction workers in two realistic scenarios: (1) Self-care needs when experiencing heat exhaustion (Figure 1); (2) How to assist a coworker who is experiencing heat exhaustion (Figure 2). Figures 1 and 2 show that researchers have enriched the immersive experience by constructing a highly realistic virtual construction environment. Researchers have imported high-quality 3D models of real construction equipment, buildings, trees, and terrain. This level of detail furthers the sense of presence and engagement within the simulation, providing an effective training platform.

The process of crafting the proposed VR system commences by establishing precise *Simulation Objectives*, acting as the bedrock to ensure that every subsequent step aligns harmoniously with the intended outcomes. Once these objectives are defined, it becomes imperative to delve into the realm of *Identifying VR Hardware and Software Compatibilities and Limitations.* This phase necessitates a comprehensive understanding of the specific virtual reality tools earmarked for deployment, accompanied by a keen awareness of their respective strengths and potential constraints. It also entails a strategic evaluation of how these software and hardware components will seamlessly integrate into the final product. With the hardware and software components diligently selected, the focal point shifts towards the vital task of *Optimizing the Simulation for our Hardware*, a pivotal step aimed at guaranteeing seamless performance while diligently mitigating potential technical impediments. This encompassed a meticulous examination of hardware constraints and an adept recalibration of various elements within the simulation, including real-time shadows, lighting, particle effects, render distance, and level of detail (LOD).

Figure 1. Self-care needs when experiencing heat exhaustion scenario.

Figure 2. Assisting a coworker who is experiencing a heat exhaustion scenario.

The momentous decision of selecting the underlying framework is tackled through the process of *Identifying Compatible 3D Engines*, recognizing its profound influence on the simulation's capabilities, performance, and development timeline. With the technical groundwork firmly established, the subsequent phase heralds the commencement of *Level Design*. Within this arena, virtual environments take shape, with thoughtful consideration given to spatial configurations, interactive elements, and overarching user objectives. Intrinsic to any successful simulation is a user-centric design ethos, exemplified by judicious choices made to *Ensure Ease of Use*, *Accessibility*, *and Intuitiveness.* These choices are geared towards creating a seamless experience, particularly catering to users who may be venturing into the realm of virtual reality for the first time. The essence and ambiance of the simulation are meticulously fashioned during the *Environmental Design phase*, deftly crafting the desired atmospheric tone.

In consonance with the research's nature, meticulous selections, such as employing warmer lighting hues and introducing pronounced shadows, were made to evoke a sense of warmth. In parallel, the pivotal role of *Sourcing 3D Models* assumes significance, as these models populate the virtual realm, infusing it with dynamism and authenticity. As these designs meld into the environment, it becomes imperative to *Implement Collision Detection and VR Interaction Capabilities*, enabling users to interact with and manipulate objects, all while being seamlessly tracked by both the user and the virtual camera. *The UI/UX phase* marks a crucial juncture in ensuring the system's intuitiveness and ease of use. User Interface (UI) elements are thoughtfully deployed to guide users through their journey, offering essential progress indicators and initial instructions. Elevating the immersive experience, *Audio Sourcing* enriches the simulation by providing additional information through audio prompts, both before, during, and after the virtual experience. Through astute utilization of the *Oculus Interaction SDK*, the virtual reality headset is seamlessly linked to the meticulously designed environment. Ultimately, this extensive process culminates in Software Deployment via MQDH, facilitating the distribution and local installation of the simulation on user devices, making it readily accessible to the intended audience. Figure 3 shows a block diagram that reflects the approach to the development of the VR application.

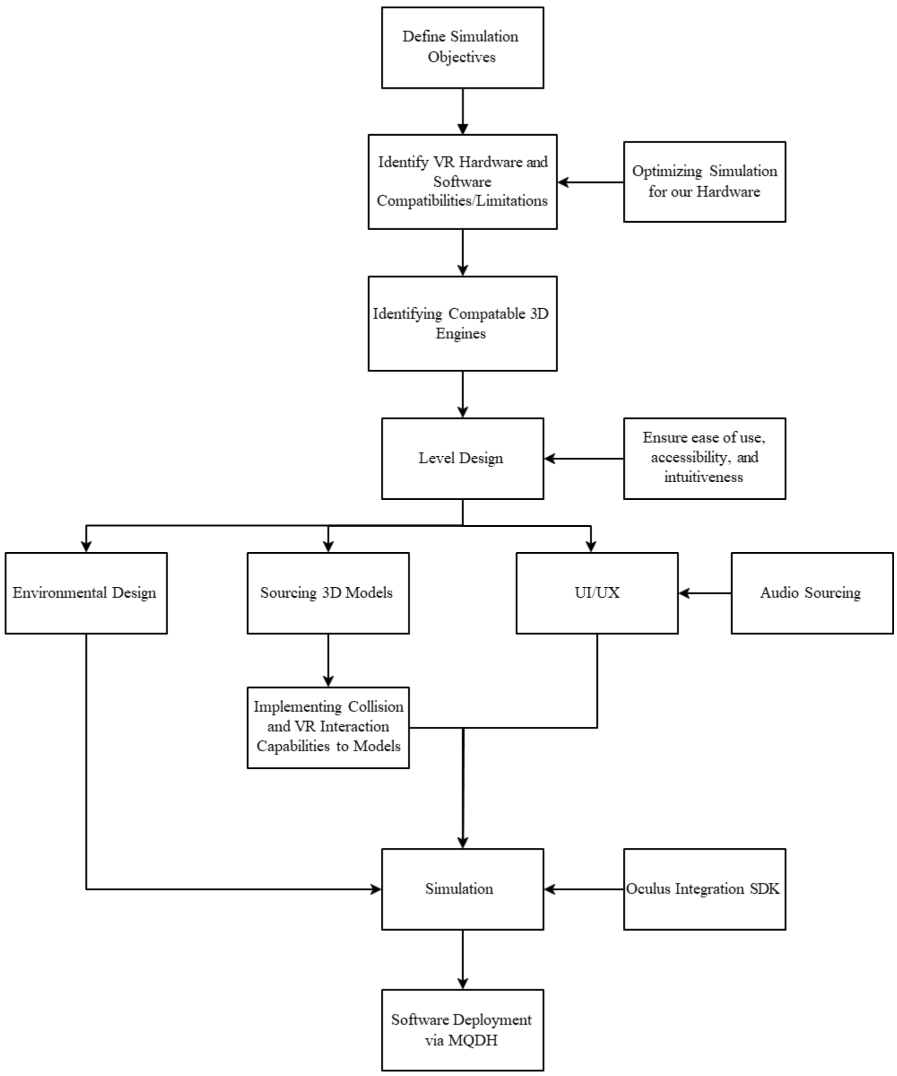


Figure 3. A block diagram that reflects the approach to the development of the VR application.

The training system, tailored for Meta Quest 2, leverages Unity3D, facilitating the creation of a dynamic, three-dimensional environment for trainees. Visual Studio 2022, our chosen integrated development environment (IDE), optimizes coding and debugging and has supported interaction with Unity3D. We have incorporated a Meta-provided software development kit (SDK) to enhance the software with virtual reality hand tracking and spatial tracking. The final software is deployed via Meta's Meta Quest Developer Hub (MQDH) for user-friendly wireless integration.

A key feature of our immersive simulation is hand tracking. This function allows users to manipulate objects in the virtual environment, mimicking real-world interactions, thus removing the abstraction often associated with typical VR controllers. To further enhance realism, the objects within our 3D environment obey the laws of physics, allowing users to experience naturalistic actions such as grabbing, handling, or dropping items.

To navigate the virtual environment, the researchers employed an intuitive gesture-based system. Users can easily teleport to different sections of the environment by simply pointing and clicking. This action creates a white arc, showing the user their destination before they make the transition, as shown in Figure 4, and is introduced to trainees through a straightforward tutorial before they begin the experience.

(**a**) (**b**)

Figure 4. (**a**) Users can easily teleport to different sections of the environment by simply pointing and clicking; (**b**) This action creates a white arc, showing the user their destination before they make the transition.

As illustrated in Figure 5, the accurate sequence of steps outlining the interactions between trainees and objects within the training scenarios is documented below:

Scenario 1: Experiencing Symptoms of Heat Stress.

Step 1: Drink Water—The initial step is to hydrate by drinking water. Small sips are more effective and less shocking to the system than large gulps.

Step 2: Put on Personal Protective Equipment (PPE)—Put on your PPE (hard hat in this case), if you haven't already, to add an extra layer of protection against heat stress.

Step 3: Go to Designated Shaded Area—Relocate to a pre-designated shaded area to minimize exposure to environmental heat stressors.

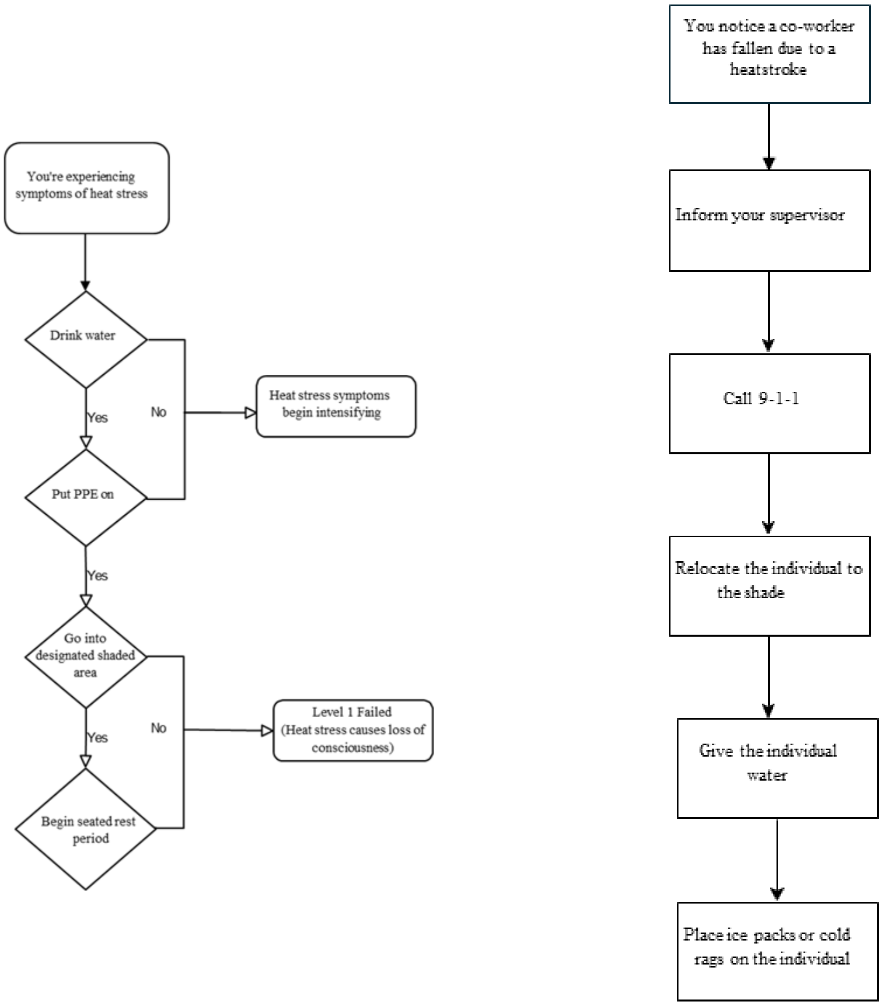
Step 4: Begin Seated Rest Period—Once in the shaded area, rest sitting down for at least 5 min. This rest is not merely a break but a necessary part of mitigating the symptoms of heat stress.

Scenario 2: Coworker Has Fallen Due to Heatstroke.

Step 1: Inform Your Supervisor—The first action you should take is to inform your supervisor. This ensures that the incident is properly documented and that additional resources can be mobilized if needed.

Step 2: Call 911—Once the supervisor is aware, immediately call emergency services and request medical assistance to your location.

Step 3: Relocate the Individual to the Shade—As you wait for emergency services to arrive, move the individual to a shaded area to minimize further heat exposure.
Step 4: Give the Individual Water—Offer water to the individual, encouraging them to take small sips to combat dehydration.
Step 5: Place Ice Packs or Cold Rags on the Individual—Use ice packs or cold, wet rags, particularly around pulse points like the neck, armpit, and groin areas, to help lower body temperature more quickly.



(a) (b)

Figure 5. (**a**) Steps to do Scenario 1: Experiencing symptoms of heat stress (left-hand side); (**b**) Steps to do Scenario 2: Coworker has fallen due to heatstroke (right-hand side).

The proposed VR system introduces several novel features to the existing body of knowledge. First and foremost, significant improvements were made to the Oculus integration libraries, enhancing the overall user experience by making it more intuitive and effective. Notably, this research focuses on the refinement of the object interaction and physics system, a key innovation. This system was meticulously designed to monitor the user's position within the virtual environment and to detect user interactions with objects. Beyond merely identifying user actions, such as drinking water or donning a hard hat, it also discerns the user's precise location within the environment. We actively track the user's 3D coordinates to trigger specific events, such as audio prompts or animations, when they enter specific locations in the 3D environment. This functionality ensures that the training simulation progresses seamlessly without the need for external input from an instructor, thus maintaining the user's immersion throughout the simulation. These systems were not readily available in open-source libraries and necessitated tailored development to align with the requirements of our research.

Furthermore, the researchers made crucial adaptations to the teleportation mechanism inherent to the Oculus Integration library to better align with our project's objectives. Notable among these modifications is the restriction of the user's teleportation abilities. We strategically placed "hot spots" at points of interest, offering users guidance on where they should proceed while preventing them from deviating off course. These zones are designated for specific training modules, such as tables with interactable objects or safe relocation areas for individuals experiencing heat stress. These enhancements aim to make training sessions more instructive and user-friendly. In terms of Oculus Hand Tracking within the Oculus Integration for Unity library, we implemented improvements to depict the user's hand positioning and movements with greater precision. This involved the individual calibration of each finger and customization of their responses to object collisions within the simulation. These changes result in a more accurate and immersive experience than what is typically available in the standard library.

Moreover, we developed highly realistic hand models that dynamically change as heat stress symptoms progress. At the onset of the simulation, participants undergo the initial stages of heat stress. As training time elapses without the participant taking steps to alleviate heat stress, noticeable changes in the skin's vasculature, such as redness or the appearance of rashes, become evident. To further simulate the effects of heat stress, we implemented customizations to the OVRCameraRig within the Oculus Integration for Unity library. These alterations allowed us to apply visual effects on top of the existing stereoscopic display. For instance, as time progresses during Scenario 1 without the user actively mitigating heat stress, visual effects like blurred vision, reduced peripheral vision, and slight color degradation are introduced. These effects serve to enhance the realism of heat stress and are deemed crucial for amplifying both immersion and learning outcomes within the simulation.

4. Evaluation and Assessment

The effectiveness of the suggested VR method was evaluated via multiple training workshops for 82 construction workers from two companies, as shown in Table 1.

Table 1. The training participants.

Company	Number of Trainees
Company A	39
Company B	43
Total Number of Trainees	**82**

Company A participants took part in a traditional training session using PowerPoint slides and a frontal lecture. Company B participants took part in a VR training session using the interactive system this study developed, as shown in Figure 6.

(**a**) (**b**)

Figure 6. (**a**) Company A participants took part in a traditional training session; (**b**) Company B participants took part in a VR training session.

Both company A and B participants took a pre- and post-assessment survey comprising six questions. The pre-assessment test was leveraged to establish a baseline across the two experimental groups. Further, a Mann–Whitney U-test was performed to evaluate the possible difference in the prior knowledge of students across two groups. The test substantiated that there was not any significant difference between the knowledge of students across the experimental groups before attending the learning sessions (p-value = 0.4765 > 0.05).

The post-assessment test results were utilized to identify potential distinctions between the two learning setups. Table 2 illustrates a substantial reduction in incorrect responses to all questions following VR training when compared to conventional training. Furthermore, we conducted a Mann–Whitney U-test on the scores obtained from the post-test to establish any statistical significance between the two instructional approaches. The test confirmed a statistically significant variance in student learning outcomes between VR training and traditional training (p-value = 0.00152 < 0.05).

Table 2. The results of the post-assessments for traditional training vs. VR training.

	Total No. of Wrong Answers					
	Q.1	**Q.2**	**Q.3**	**Q.4**	**Q.5**	**Q.6**
Traditional Training Post-Assessment	11	15	11	9	4	1
VR Training Post-Assessment	5	2	6	6	1	0

5. Discussions and Conclusions

The findings of this pioneering study, which advocates for the adoption of an interactive VR application for heat stress training in the construction industry, hold immense potential for implementation in various industries and by academic researchers alike. From a managerial perspective, the integration of VR-based training has the power to revolutionize safety practices in the construction industry. By immersing construction workers in highly realistic scenarios enriched with detailed 3D models of construction equipment, buildings, trees, and terrain, VR training creates a dynamic learning environment. Workers experience heat stress scenarios firsthand, enabling them to recognize the signs of heat exhaustion and adopt preventive measures in a controlled and safe setting. This approach not only enhances knowledge retention but also builds muscle memory and mental preparedness, equipping workers to respond promptly and effectively during actual heat-related incidents on construction sites. To implement this approach effectively, construction managers should collaborate with researchers and regulatory bodies such as OSHA. Seeking support and resources from these organizations can aid in the development and implementation of comprehensive VR training programs across the construction industry. Emphasizing the importance of safety and investing in advanced training methodologies can foster a culture of safety consciousness among workers, ultimately leading to reduced accidents, injuries, and fatalities related to heat stress. Additionally, managers should address the study's identified limitations, such as conducting larger-scale studies to ensure the generalizability of results and exploring cost-effective solutions to make VR training accessible to all construction companies and workers.

In academia, the study's contributions are significant in advancing the theoretical understanding of the efficacy of VR-based training for heat stress prevention. The research provides empirical evidence supporting the effectiveness of immersive training methodologies in preparing workers to handle heat stress situations. This evidence can serve as a foundation for future research endeavors, encouraging academics to delve further into the potential applications of VR training in other safety-critical domains. Moreover, researchers should focus on longitudinal studies to assess the long-term impact of VR training on knowledge retention and skill application. Understanding how VR training influences worker behavior and decision-making over extended periods can shed light on its sustainability and long-term benefits. As technology continues to evolve, academic researchers should also investigate the integration of multi-sensory elements into VR training. Combining visual, auditory, and tactile stimuli can further enhance the realism and im-pact of the training experience, reinforcing learning and improving knowledge retention. By tapping into the potential of multi-sensory engagement, researchers can unlock new avenues for advancing VR training methodologies and improving the overall efficacy of safety training programs.

Furthermore, exploring the customization of VR training modules to cater to individual worker's needs and skill levels can enhance the training's effectiveness. Tailoring the training experience can lead to higher engagement, ensuring that workers internalize the knowledge gained during VR simulations and apply it effectively on the job. Lastly, expanding the application of VR-based training to address other occupational hazards in construction and beyond can contribute to creating a comprehensive safety training framework. By leveraging VR technology to train workers in various safety-critical situations, industries can equip their workforce with a diverse set of skills to manage a wide range of risks effectively. Researchers should explore the adaptability of VR-based training to different work environments and hazard types, ensuring its relevance and applicability across various industries and job roles. Further, to enhance the realism of the suggested VR heat stress training system, future research could introduce thermal effects that simulate the sensations of heat experienced in real-life situations. This innovation would provide users with a more immersive and educational experience by replicating the physiological responses to heat stress, helping them understand its impact on performance and decision-making.

This study's findings on VR-based heat stress training represent a significant step forward in advancing occupational safety practices, particularly in the construction industry. The successful implementation of VR training can revolutionize safety standards by providing workers with immersive and effective learning experiences. Managers, researchers, and industry practitioners should collaborate to address challenges, capitalize on opportunities, and drive the widespread adoption of VR-based safety training. Through continued research and innovation, VR training has the potential to revolutionize safety practices across industries, fostering a safer and more informed workforce while reducing the prevalence of workplace accidents and injuries.

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