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Effectiveness of Immersed VR Technology in Construction Safety

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ABSTRACT
This study addresses the persistent gap between theoretical knowledge and practical application in construction safety training by designing and evaluating an immersive Virtual Reality (VR)-based training module for novice Indian front-line supervisors. Despite the high-risk nature of the construction industry, traditional lecture-based methods often fail to achieve the necessary procedural knowledge transfer, particularly regarding the correct selection and use of Personal Protective Equipment (PPE). We employed a multi-phased methodology involving the development of a high-fidelity, interactive VR simulation using Unity and Blender, which modelled a realistic construction site and required users to select the correct PPE from valid and distractor options. Testing with supervisor students, who initially demonstrated minimal practical PPE knowledge, showed a marked improvement in selection accuracy following repeated self-paced VR practice, supported by immediate visual feedback. Post-training assessment revealed strong user acceptance and significant learning gains: 92% of participants rated the training as Very helpful or extremely helpful for learning safety procedures. Furthermore, participants reported high levels of realism (92% Very or Extremely realistic), engagement (96% Very or Extremely engaging), and a significant boost in confidence (92% Very or Extremely confident) for on-site PPE application. The results provide empirical evidence that immersive VR is a superior pedagogical tool, effectively bridging the knowledge-to-action gap by fostering procedural memory and situational awareness in a risk-free environment. Our present research supports the implementation of environmentally and realistically appropriate virtual reality (VR) solutions for construction safety education in order to improve productivity and, eventually, lower workplace dangers.
KEYWORDS: *Virtual Reality, Training academy, Immersive Training, Simulation, Engagement, Safety Procedure, Site Environment, Work Productivity, Hazards, Real world Application*

INTRODUCTION

The considerable improvements in managerial methods and innovation, the construction industry is widely regarded as to be among the most hazardous, having a numbers percentage of worker death and injury continuing to exist. Places of work are fast-paced, complicated, and unexpected, which makes them difficult to manage. Setting for preserving worker safety. Although there have been advancements as a result of conventional safeguards like rules, the availability of specialized clothing and equipment (PPE), and compliance supervision, these initiatives frequently fail because primary executive effective risk identification and instructional effectiveness are limited.

Its separation within its implementation of protective measures becoming a conversion of conceptual understanding towards safer workplace behavior is becoming more and more obvious. Traditional methods of protective guidance, tend to involve seminars, moving instructional tools, and with animations are commonly criticized due to their poor modelling of actual circumstances as well as lacking in interaction [5]. These approaches have trouble keeping novices interested, which frequently leads to inadequate recall to significant processes and an incapacity to react appropriately for changing threats on the job area. According to recent studies, contextual of circumstances for hands-on training seem crucial for encouraging long-lasting behavioural changes and efficient risk mitigation in construction staff [6-7].

Therefore, it remains a general demand for unique learning approaches that effectively involving managers or employees in real-world risky scenarios in addition to providing information, thereby encouraging the proper use of personal protective equipment (PPE) with attention to precautionary procedures [8–10]. According to this regard, immersive VR (virtual reality) has become a game-changing technology that makes it possible to create dynamic, incredibly feasible teaching settings that virtually resemble real building sites. Through the use of virtual reality (VR) tools, novices may train identifying unique to hazards, participate in harmless digital worlds, and get right away feedback on their choices of action [11–13].

Comparing virtual reality security instruction with standard techniques, regulated experiments suggest the fact this method not just raises operational adherence as well as understanding remembering but additionally greatly increases the ability of participants to recognize risks and choose the right personal

protective equipment [14–16]. The capacity of VR to deliver repeatable, contextually rich experiences supports deeper cognitive immersion and muscle memory development, critical to effective safety behaviour in live site conditions [17].

In addition, VR platforms can be integrated with digital twin technology, providing dynamic, up-to-date replicas of construction sites that enable the continuous adaptation of training scenarios to reflect changing site realities. Such integration fosters a proactive safety culture by supporting real-time risk assessment, interactive learning analytics, and data-driven decision-making. Instructional design principles in VR environments—such as high realism, active user engagement, and adaptive difficulty—have been shown to reduce trainee anxiety and improve both psychological immersion and practical skill acquisition [14]. These benefits are particularly relevant for novice supervisors, who often struggle to bridge the gap between theoretical education and on-site application.

Despite the proven advantages, barriers to widespread VR adoption remain, especially in resource-constrained settings where contextualization to local safety regulations and economic realities is often lacking [14-15]. According to recent study, it has become imperative as VR material be financially, conceptually, and socially appropriate in order to comply about regional building codes as well as administrative requirements [16–17]. Additionally, although important at the starting point of deployment, expenditures remain frequently exceeded with the longer-term advantages of better-quality results along with lower incident-related costs. current research intends to develop and assess a comprehensive virtual reality-based precautionary training program especially for Indian construction workers in light of these possibilities and limitations. The section's objectives aim to improve hazards identification abilities, raise knowledge about personal protective equipment (PPE), and close the knowledge separation across classroom theory and job-site preparation. present research aims to provide solid evidence in Favor of the continued incorporation of immersive technologies in international construction safety programs by investigating their efficacy via systematic evaluation with viewer from users.

METHODOLOGY

Research Design and Approach

Our investigation used a sequential strategy to assess the uptake of comprehensive virtual reality (VR) technology as a tool of instruction for risk instructing and to look into the shortcomings associated with front-line staff's present safety during building training techniques. The approach combines cycles for planning, implementation, and execution that are informed from both experience execution and research evaluation.

VR Platform Architecture

Combination of modern equipment and tools makes it easier to create digital representations of multidimensional worlds using VR (virtual reality) methods. Viewers can engage with simulated goods in present moment thanks to such invention, which replicates experience. Sensations and actions that are similar to those that are found in actual environments. Through precise simulation of item relations and surrounding behavior, virtual reality (VR) improves the consumer's experience of occurrence and creates an engaging experience that simulates realism in a completely realistic virtual world. Many of the riskiest industries is construction, with a high rate of injuries and risky job procedures are typically caused by a lack of training for staff. Virtual reality (VR) models offer a secure and interesting environment for practicing danger recognizing, appropriate apparatus use, and conforming to prevention regulations. With the use of thorough concepts obtained Based on earlier research, a user-focused virtual reality preparing framework developed for inexperienced front-line supervisors, emphasizing the vital role that personal protective equipment (PPE) plays in protecting workers at work. By interactive engagement, this methodology aims to promote experience learning and the automaticity of safety behavior that are necessary for on-site implementation.

VR Simulation Technology

A capable designing games platform called Unity was used to create the training module because of its cross-platform interoperability, ongoing rendering capabilities and simplicity to interface to external modelling software. A three-dimensional realistic simulation of real construction zones served as a framework for the virtual reality experience. To accurately depict real-world spatial situations, field photos and site-specific layouts were digitally recreated in Fig 1.

Fig.1: Construction Site

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scripting enabled environmental dynamics such as smooth movement, collision detection, and unobstructed navigation, thus supporting realistic scenario interaction. At the virtual site's entrance, a digital bench was populated with essential personal protective equipment (PPE) items, requiring users to equip themselves correctly before site entry.

3D Asset Development

Blender software was employed for the precise modelling of PPE components, including helmets, jackets, safety shoes, goggles, and gloves. Selection criteria for these assets were rooted in OSHA 1910 Subpart I standards and local field observations. To test decision-making and focus, distractor objects resembling genuine PPE in appearance were introduced alongside the correct items. All assets were exported into Unity and configured for interactive use.

Training Workflow

The design prioritised the creation of a user-friendly VR training model, specifically emphasising the proper selection and use of basic PPE for new construction personnel. Training scripts were designed to promote experiential learning and develop procedural memory, ensuring safety behaviours become automatic in future real-world situations. Blender software was utilised to model five specific PPE types—helmet, jacket, safety shoes, goggles, and gloves—to achieve geometric and visual accuracy. Distractor objects were incorporated to test the user's ability to differentiate correct PPE based on function rather than solely colour or appearance. Asset Integration and Scene Setup: Modelled 3D assets were integrated into Unity in Fig.2. A virtual bench containing both correct PPE and distractor objects was placed to require users to equip themselves correctly before entering the simulated site.

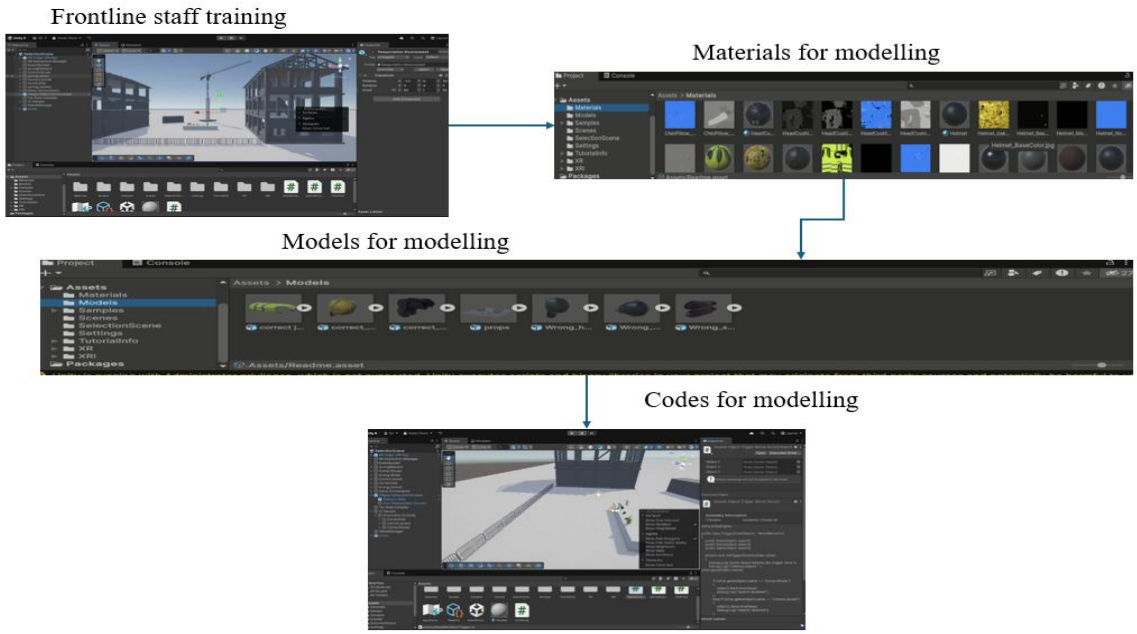

Fig.2: VR Modelling

Scene and Asset Configuration

Various construction site simulation scenarios were organised in Unity, displayed via a project list interface. Textures, models, scripts, and supporting resources were managed in Unity's asset panels. Settings for position, scale, and rotation were configured per asset to ensure environmental realism.

Interactive Training Scripts

Programmed scripts guided experiential learning by prompting users to identify and select appropriate PPE under simulated site conditions. Dynamic feedback, including colour cues and notification symbols, indicated correct or incorrect choices—reinforcing procedural memory through user interaction.

Assessment and Evaluation

The VR model was tested with labourers who had previously completed a survey. A structured feedback section was conducted after the interaction using questionnaires and group interviews to assess usability, learning outcomes, and perceived usefulness. The evaluation focused on three key areas: ease of navigation and interaction in the VR environment, clarity of safety messages, and improvement in hazard identification and PPE recognition, as in Fig.3.

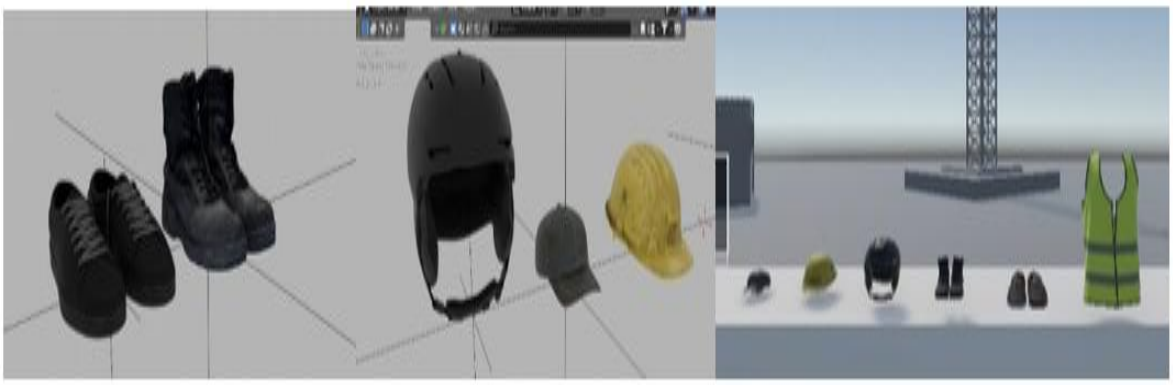

Fig 3: Safety Equipment Dashboard

Implementation and User Testing

Participants were recruited from a training institute and represented beginners with minimal prior construction experience. Using a head-mounted display (HMD) linked to a laptop, participants immersed themselves in the VR training environment, enabling full navigation and object interaction within the simulated site. Real-time evaluator monitoring was achieved through mirrored screens, allowing for live assessment and session recording. Each action and decision made by participants was logged for analysis.

Feedback and Performance Metrics

Structured questionnaires and group interviews collected qualitative data on navigation, usability, message clarity, and improvements in PPE identification and hazard awareness. The assessment focused on:

1. Ease of interface navigation and object interaction
2. Comprehension and retention of safety protocols
3. Engagement and motivation compared to traditional training
4. Knowledge gain in hazard recognition and PPE use

The questionnaires used for the study:

1. How realistic did the VR environment feel?
2. Did interacting with the VR environment feel natural?
3. How confident are you in identifying the correct PPE after VR training?
4. How confident are you in using PPE correctly on a real site after VR training?
5. How helpful was VR in learning safety procedures compared to lectures/reading?
6. How well do you remember the steps for using PPE after VR training?
7. How easy was it to navigate the VR environment?
8. How easy was it to interact with objects in VR?
9. How engaging was the VR training?
10. Would you recommend VR training to other beginners with no site experience?

Ethical Considerations

All participants provided informed consent. The data were anonymised and treated confidentially in accordance with institutional research guidelines. The study avoided any real-world risk, relying solely on simulated environments for all training activities.

RESULTS AND DISCUSSION

The study participants consisted of front-line supervisor students with limited prior exposure to real-world construction site environments or formal practical safety training. Initial observations confirmed that their knowledge regarding the practical identification and differentiation of Personal Protective Equipment (PPE) was minimal, highlighting the inadequacy of traditional, theory-based instruction.

The VR training module was designed to test procedural knowledge by requiring participants to select and equip the correct PPE (safety helmet, shoes, jacket) from a selection of valid and visually similar distractor objects. This design ensured that successful identification relied on functional knowledge rather than simple colour or shape recognition. Performance tracking within the VR environment demonstrated a marked improvement in PPE selection accuracy:

1. Participants frequently exhibited hesitancy and made incorrect initial selections for key items such as safety helmets and boots, often confusing certified PPE with non-safety-rated alternatives. Immediate visual feedback (red signal for incorrect, green for correct) was provided as shown in Fig. 4.
2. In post-practice, following repeated, self-paced practice cycles within the VR environment, participants consistently and accurately selected the required PPE. This shift suggests that the experiential, real-time feedback mechanism effectively facilitated the development of procedural memory and correct decision-making patterns.

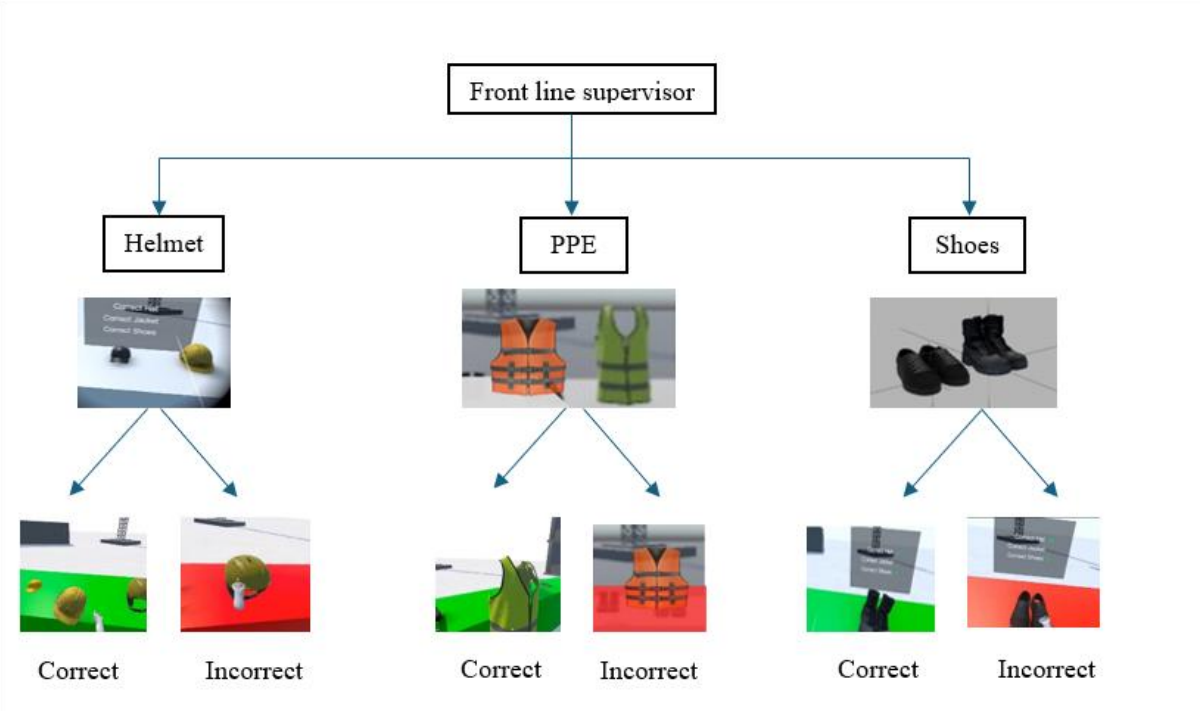

Fig 4: Selection flow of equipment

VR Immersion, Usability, and Engagement

User acceptance and the quality of the immersive experience were exceptionally high. Participants overwhelmingly rated the VR environment's realism, with a combined (64% Extremely realistic, 28% Very realistic) finding it highly reflective of a real construction site. Similarly, (60% Completely, 32% Mostly) reported that interacting with the environment felt natural. This high telepresence is critical, as the qualitative data noted, for convincingly replicated construction environments, creating strong immersion in Table 1.

Table 1: Qualitative data for usability and engagement of VR

Metric	High Rating (Very/Extremely)	Qualitative Insight
Realism	92%	VR convincingly replicated construction environments, creating strong immersion.
Natural Interaction	92%	Students could intuitively interact with objects, enabling smooth hands-on learning.

Engagement	96%	The training maintained high attention and motivation throughout.
Ease of Navigation/Interaction	84% / 76%	VR controls did not hinder learning, allowing focus on safety skills.

The training was also highly engaging, with (60% extremely, 36% very) rating it as such, confirming the system's ability to maintain high attention and motivation throughout. Furthermore, the technology presented no significant barrier to use; a substantial majority of participants found both navigation (easy/very easy) and object interaction (easy/very easy) to be straightforward, indicating a user-friendly design that did not hinder learning, allowing the focus to remain on safety skills.

Impact on Confidence, Recall, and Practical Competence

The most significant finding relates to the observed learning gains and the resulting boost in self-efficacy, directly addressing the study's core objective of enhancing practical knowledge.

Table 2: recall and practice competence

Metric	High Rating (Very/Extremely)	Qualitative Insight
Confidence in PPE Identification	92%	VR training improved recognition of essential PPE items even in beginners.
Confidence in Real-Site PPE Use	92%	VR enhanced procedural confidence in PPE use, preparing students for real-site tasks.
Helpfulness vs. Lectures	96%	VR was perceived as more effective than traditional classroom-based learning.
Recall of PPE Steps	92%	VR promoted strong retention of safety procedures and step-by-step recall.

Confidence levels in PPE knowledge and application showed a marked improvement post-training, with a majority of participants reporting they felt very confident or extremely confident in both identifying the correct PPE and in using PPE correctly on a real site. This is a critical validation of the experiential learning model, demonstrating a perceived readiness for practical application, where traditional methods had failed, as in Table 2.

This confidence correlated with strong procedural memory, as of participants reported remembering the steps for using PPE Well or very well after the VR exercise. This performance directly results from the system's interactive features, where the observed immediate visual feedback within the simulation reinforces correct behaviours and corrects initial errors, a mechanism vital for the development of procedural memory.

Pedagogical Value and Recommendation

The VR system was judged to be a superior pedagogical tool. An overwhelming number of participants found the VR training very helpful or extremely helpful compared to traditional lectures/reading. This finding strongly supports the qualitative assessment that VR was perceived as more effective than traditional classroom-based learning.

Finally, the acceptance of the technology for industry integration was decisive, with 56% yes, 36% probably yes, of students stating they would recommend the VR training to other beginners with no prior site experience. This high intent to recommend confirms the strong user satisfaction and validation of the VR module as a scalable, desirable, and effective solution for entry-level safety education.

In summary, the VR training effectively utilised a high-fidelity, interactive environment to overcome the limitations of traditional lecture-based training. It fostered high realism and engagement, resulting in measurable improvements in procedural knowledge, confidence, and recall, thus proving its utility in closing the critical knowledge-to-action gap in construction safety.

The pre-training knowledge deficit observed in participants, who were generally unable to correctly identify essential PPE despite prior academic exposure, underscores a critical limitation of traditional safety instruction. Lecture-based methods often fail to create the cognitive and contextual immersion necessary for the transfer of theoretical knowledge into actionable, procedural skills. Through providing a safe, harmless atmosphere in which repeating and learning through trial and error may take place free of tangible hazards, the virtual reality (VR) system effectively fills the vacancy. Green and red indication, this virtual world's immediate reaction mechanism, is essential for immediately clearing misunderstanding and boosting appropriate behavior, which results in an apparent enhancement in realistic efficiency over

time. Performance of the VR is largely attributed to its excellent evaluations regarding accuracy, smooth conversation, and active participation. development of precise scenario understanding together with security judgment requires high visibility, or the sensation of experiencing reality in a virtual setting. Training offered benefits are simpler to applied on an authentic job site whenever the simulating scenario closely matches actual situations, as shown by participants comments. Additionally, the considerable amounts of involvement imply that virtual reality instructional is more motivating than inactive approaches by nature, which is crucial for guaranteeing a large number and long-term learning in academic settings. One important operational result has been the observed rise in participants trust when recognizing and appropriately utilizing Equipment. On moving job sites, optimism gained by practical training is essential for guaranteeing effective and preventive safety behavior. This assurance, along with the strong desire to offer the training, shows that virtual reality is not only a useful tool however one that is both affordable and appealing for businesses to adopt.

CONCLUSION

This data investigation showed that immersive virtual reality (VR) is a helpful training technique for improving construction safety instruction for inexperienced Indian front-line workers. The virtual reality simulation greatly increased individuals' procedural understanding, operational ability, and own satisfaction by utilizing real-world site settings and demanding precise Personal Protective Equipment (PPE) choosing according to manipulated circumstances. Within subjects during which regular instructional techniques had repeatedly failed, the framework's engaging features in especially the addition of disruptive elements, current visual assistance, and frequent training possibilities proved crucial for fostering procedural memory and reinforcing safe actions.

- A frequent shortcoming of traditional formal training, that users' vital lack of realistic personal protective equipment (PPE) expertise was successfully resolved by the VR simulations.
- Throughout interacting VR training, users demonstrated a notable, observable increase in choosing PPE reliability, demonstrating that the system has the ability to promote procedural understanding alongside secure choice-making
- Qualitative review of the instruction was largely favourable, including favourable evaluations regarding efficacy, realistic feel, and participation, indicating that virtual reality is a very inspiring and adaptable instructional tool.
- Participants' assurance of recognizing as well as appropriately utilizing personal protective equipment (PPE) on an actual construction site increased significantly as a result of the practical training, which is essential for preventative prevention with safety standards.
- The research investigation offers tangible proof which comprehensive virtual reality (VR) is a great tool for instruction that fosters critical situation of situations and transferable translation in a realistic, safe setting.
- Evaluate how effectively knowledge and procedural skills are retained several months after VR training compared to conventional methods.
- Develop advanced VR modules to train users in more complex scenarios, such as fall-hazard recognition, scaffolding inspection, and emergency response, leveraging the full capability of risk-free simulation.
- Conduct a comprehensive cost-benefit analysis comparing the initial VR investment against long-term savings derived from reduced accident rates and improved training efficiency.
- Advocate for the widespread integration of culturally and practically tailored immersive technologies to foster a data-driven safety culture and achieve sustainable reductions in occupational injuries.

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