



Virtual reality safety training and auditing in warehouse environments: AHP and critical thinking approach

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Abstract

This study investigates how virtual reality (VR) can transform safety training, risk management, and auditing techniques in warehouse environments, using a mixed-methods approach to deliver practical guidance for industry and VR developers. The analysis applies four phases. The first phase involves observational studies to identify current safety practices, risk management strategies, and audit techniques. Semi-structured interviews with 15 safety experts for empathy mapping and the Delphi Technique with 10 experts to populate the 9-Window framework, assessing training needs and VR integration. The third phase utilizes critical thinking (CT) questions to analyze VR features, and the fourth phase applies the Analytic Hierarchy Process (AHP) to rank VR feature priorities based on their impact and feasibility. Observation findings indicate significant gaps in current safety practices and safety training. Semi-structured interviews and CT discussions demonstrate that VR training significantly enhances safety skills and auditing capabilities and fosters proactive risk management. Immersive VR allows trainees to utilize VR features, such as simulation of misplaced items, risk identification, voice instructions, interaction, and navigation, which were emphasized as crucial components. Furthermore, AHP results show that simulation realism and immersive interaction are the most critical factors for effective VR safety training. Overall, the study highlights VR training as a valuable tool for designers and users in enhancing warehouse safety management, auditing skills, and risk management practices. However, limitations include the need for broader risk scenario training in VR. Future research should quantify training effectiveness and compare it with conventional methods.

Keywords Virtual reality · Safety training · Auditing · Risk management · Analytic hierarchy process (AHP) · Critical thinking (CT)

1 Introduction

The supply chain and logistics sector encompasses warehouse environments that present significant safety risks due to their intricate operations and continuous interaction between workers, materials, and machinery. These hazards contribute to substantial resource damage and, in severe cases, loss of life. Safety training maintains operational efficiency and minimizes the severity and the likelihood of workplace risks. The US Bureau of Labor Statistics (BLS) reports that fatal workplace injuries in the United States increased 18.54% between 2012 and 2022 (US 2023). Therefore, this sector requires adopting robust safety training methods to protect workers from the increasing risk factors exacerbated by the complexity of warehouse operations and industry expansion (Vukićević et al. 2021).

According to the Occupational Safety and Health (OSH) (Di Prinzio et al. 2021), safety training minimizes

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workplace hazards and assures employee well-being. Gao et al. (2019) and Beer and Mulder (2020) mentioned that adopting advanced technologies with realistic and interactive training scenarios significantly improves occupational safety and health (OSH) practices. These approaches allow workers to practice risk management procedures along with cognitive skills such as problem-solving and decision-making.

VR enables participants to engage in realistic environments, thus enhancing their safety skills, auditing techniques, and risk management capabilities (Vukićević et al. 2021; Bernabei et al. 2024). Previous research demonstrates that VR is an effective training tool where it improves skills and learning outcomes within a safe environment (Guo et al. 2024; Makransky and Petersen 2021). This is achieved through a learning-by-doing methodology, which emphasizes experiential learning in a controlled and realistic environment (Conesa et al. 2024). Since industrial operations have grown more complex, it is essential to integrate the latest innovations like VR to identify and mitigate risks according to safety standards. Costantino et al. (2021); Beer and Mulder (2020).

According to Makransky (Makransky and Petersen 2021) and Toyoda (Toyoda et al. 2022), VR training improves risk identification, cognitive engagement, and skill retention through immersive learning environments. Moreover, integrating the Cognitive-Affective Model of Immersive Learning (CAMIL) (Makransky and Petersen 2021) and Expectancy-Value Theory (Wigfield 1994) into VR-based training programs enhances motivation and learning outcomes. These frameworks provide a deeper understanding of how immersive experiences impact safety awareness and behavior change among workers. Using these advanced training methodologies, the logistics and supply chain sector offers its employees customized safety training to navigate the complexities of warehouse operations, thus reducing accidents and enhancing safety culture.

1.1 Research questions

The study aims to develop a framework for implementing VR safety training to enhance safety compliance in warehouse environments, with applicability to other industries facing similar challenges. Therefore, this research investigates the following questions:

Inductive questions explore current and future aspects of VR safety training, gathering information from observations and input from stakeholders to predict VR benefits. In contrast, detective questions assess expert opinions and theoretical models, evaluating how existing knowledge can be applied to warehouse VR safety training.

- RQ 1: What specific safety practices and hazards are prevalent in warehouse environments? (Observation) (Inductive)
- RQ 2: How are risk management strategies and safety audit procedures implemented to mitigate hazards in warehouse environments? (Observation) (Deductive)
- RQ 3: What are experts' perceptions regarding the effectiveness of VR training? (Empathy map) (Inductive)
- RQ 4: How can VR be effectively integrated to address safety training needs? (Empathy map) (Deductive)
- RQ 5: How do the current capabilities of VR safety training compare to systems and time? (9-window tool)? (Inductive)
- RQ 6: What are the key VR features necessary for effective safety training? (Critical thinking) (Inductive)
- RQ 7: How do specific VR features contribute to improved safety training? (Critical thinking) (Deductive)
- RQ 8: Which VR features are most effective in improving safety training? (AHP) (Inductive)

This research is conducted in four phases to provide a comprehensive approach to enhancing warehouse safety through VR training and improved safety practices.

Phase 1: Observations: This involves current safety practices, risk management, and auditing techniques that systematically identify workplace hazards and evaluate warehouse procedures to ensure safety standards compliance to mitigate risks as proactive procedures to prevent incidents from occurring.

Phase 2: Semi-structured interviews with safety stakeholders develop empathy mapping and a 9-Window framework (Lewrick et al. 2018). It is considered a tool that deepens the understanding of safety experts with VR safety training. The 9-window framework provides a structured approach to identifying past, present, and future challenges across three system levels, offering continuous improvements. This approach investigates VR opportunities in improving learning outcomes and skills. Additionally, interviews assess the benefits and limitations of current VR training practices. Furthermore, it explores the integration of VR technology in warehouse safety training and determines the necessary training interventions to identify and mitigate risks (Di Prinzio et al. 2021).

Phase 3: In-depth discussions employing Critical Thinking (CT) questions used as a qualitative tool for a deeper understanding of how VR training improves safety in warehouses. CT involves observing, analyzing, interpreting, inferring, and judging safety experts. Deep CT discussions reveal VR features that enhance safety training (Bazan Montalto et al. 2024; Facione et al. 2016) and explore enhancing safety outcomes (Vukićević et al. 2021; Potter 2022).

Phase 4: Analytic Hierarchy Process (AHP). This phase prioritizes critical VR features for safety training based on

expert perspectives (Cheng and Li 2001); for example, it has been used to enhance safety training (Shringi et al. 2023), and optimal VR engine selection (Bourhim and Cherkaoui 2020). Where AHP is an effective method for multi-criteria decision-making (MCDM) (Triantaphyllou 2000; Yoon and Hwang 1995), it ranks and prioritizes safety training features. It enhances analysis and decision-making skills essential for risk assessment, thereby optimizing training effectiveness and outcomes.

This research investigates VR safety training opportunities and challenges in four phases. Phase one identifies hazards and evaluates current practices through observations and audits. Phase two gathers expert perspectives through interviews to uncover training needs. Phase three utilizes deep discussions to explore key VR features and their impact on safety training outcomes. Phase four prioritizes VR features using the AHP, ensuring expert-informed and effective training solutions. This method bridges training gaps and optimizes VR's integration into warehouse safety practices.

Observations, semi-structured interviews, critical thinking, and the Analytic Hierarchy Process evaluate current training systems and identify critical features to enhance safety training using advanced technology. Integrating these methods provides a comprehensive framework to map how VR safety training addresses existing safety gaps and improves warehouse safety practices (Bader et al. 2023; Vukićević et al. 2021).

2 Literature review

Workplace environments are characterized by diverse hazards that require robust training programs to prepare employees with the proper knowledge and skills to identify, assess, and mitigate risks effectively. Virtual reality has emerged as a transformative tool for safety training in warehouses, offering immersive and interactive learning experiences (Scorgie et al. 2024). According to previous research, VR integration into organizations' training frameworks improves risk identification, promotes safety compliance, and reduces workplace accidents (Bernabei et al. 2024; Gauthier et al. 2022; Wu et al. 2020).

This literature review systematically provides a comprehensive understanding of VR's role in safety training. Recent studies emphasize the adaptability of VR in simulating complex hazard scenarios, improving decision-making, and reinforcing safety protocols through repeated exposure to diverse risk situations (Guo et al. 2024; Toyoda et al. 2022). This research goes through the following core themes:

1. **Organizational Needs:** Current safety status and hazard types in the workplace. Also, addressing safety concerns to protect lives and preserve resources.
2. **Proactive safety standards:** Integration of risk mitigation plans and auditing techniques with international safety standards.
3. **Safety training benefits:** It is important to enhance employees' knowledge, skills, and abilities to improve workplace safety.
4. **Integration of VR in safety training:** Exploring VR technological capabilities for improving safety procedures.
5. **Application of VR safety training in the logistics sector:** Focus on high-risk environments such as warehouse operations to elevate safety outcomes.

This structured approach allows for a detailed exploration of how VR transforms safety training to improve safety outcomes in warehouse environments. Bernabei's study highlighted VR's function in providing a scalable solution for safety training across industries, with significant improvements in safety awareness, hazard recognition, and employee engagement in training programs (Bernabei et al. 2024).

2.1 The importance of VR warehouse safety training

This study employs a comprehensive VR safety training framework, as illustrated in Fig. 1.

2.1.1 Organizational needs

Workplace accidents cause injuries, fatalities, property damage, and operational disruptions, leading to lost productivity. Effective safety protocols are essential to protect workers and ensure smooth operations. For instance, high-risk industries such as construction and manufacturing contribute significantly to accidents, with falls, machinery incidents, and exposure to hazardous substances being common causes (Toyoda et al. 2022). However, advancements in safety technologies, such as automation and remote monitoring, have been mitigating these risks. Therefore, implementing effective safety protocols, alongside technological innovations, is crucial to safeguarding workers and ensuring operational efficiency (Bernabei et al. 2024; Ortiz and Park 2018).

On the other hand, effective safety training aligns with organizational needs by reducing workplace risks, enhancing compliance, and promoting a culture of safety, which ultimately improves operational performance and employee well-being (Reason 2016).

2.1.2 Proactive safety procedures

Effective risk mitigation is essential to prevent accidents in high-risk work environments, such as warehouses. Proactive safety procedures involve identifying potential hazards, assessing the risks associated with these hazards, and implementing measures to reduce or eliminate these risks before



Fig. 1 Comprehensive framework for implementing workplace safety with immersive VR training

they cause harm (deVries et al. 2016; Szymonik 2024). According to Chatmon's research, proactive procedures enhance the safety culture within the workplace environment (Chatmon 2023). Yap's research explores the advanced technology's influence on improving safety outcomes (Yap et al. 2024).

2.1.3 Safety training benefits

Safety training equips workers with the required knowledge and skills to perform their tasks safely and efficiently. It is instrumental in strengthening safety protocols, emergency response procedures, and risk awareness, while also promoting behavioral change and fostering a robust safety culture. By enhancing the understanding of diverse hazards such as physical, biological, and electrical risks, safety training ensures adherence to established safety standards (Barati Jozan et al. 2023; Bęś and Strzałkowski 2024).

Jang emphasizes that effective safety training enhances workers' ability to assess risks and prepare for unforeseen events, a critical component in developing adaptive safety skills across diverse settings (Jang et al. 2016). Similarly, Miltenberger highlights that structured safety education significantly improves hazard recognition and response capabilities, particularly when tailored to specific environments (Miltenberger et al. 2020). Organizations that implement comprehensive safety training programs benefit from reduced accident rates and increased employee satisfaction, further showcasing the value of investing in evidence-based

safety education systems (Barati Jozan et al. 2023; Bęś and Strzałkowski 2024).

2.1.4 VR safety training integration

In high-risk environments, VR safety training addresses the limitations of traditional methods by offering immersive, interactive simulations that enhance engagement and knowledge retention (Scorgie et al. 2024). VR enables workers to experience realistic hazard scenarios, aligning with constructivism theory (Hein 1991) and learning-by-doing methodologies (Thompson 2010) enhancing knowledge retention through active participation.

Several studies emphasize the benefits of integrating VR into risk management training (Stefan et al. 2023; Yoo et al. 2023). Furthermore, Gauthier's study demonstrates its effectiveness in improving hazard recognition, safety awareness, and emergency response skills by providing hands-on experience that allows workers to develop better responses to emergencies and unsafe conditions (Gauthier et al. 2022). For instance, VR training has been shown to increase hazard recognition by 25%, underscoring its value in risk management and safety education (Lewczuk and Żuchowicz 2024).

Moreover, Toyoda reviewed VR-based training in high-risk engineering industries and highlighted the improvement in hazard recognition and retention of safety procedures (Toyoda et al. 2022). Toyoda also reinforced that VR systems simulate a wide range of dangerous scenarios, allowing workers to virtually experience and manage risks

before encountering them in real life. This proactive training approach improves both hazard recognition and workers' preparedness, empowering them to prevent accidents effectively. Kanade and Duffy also found that VR safety training enhances the learning process compared to conventional methods, especially for tasks requiring high precision in hazard detection and emergency response (Kanade and Duffy 2022).

Recent advancements complement VR safety training by offering immersive platforms that enhance training effectiveness in industrial environments. For instance, a mixed reality (MR) based platform integrating IoT and cyber-physical systems improves occupational safety and health training by providing realistic simulations that reduce workplace accidents (Wang et al. 2022a). Similarly, MR training for dangerous goods handling, such as the MRSafe model, addresses safety challenges relevant to warehouses with hazardous materials, aligning with the safety needs (Mystakidis et al. 2024). Additionally, MR platforms enhance user engagement and perceived value, informing VR training design to improve trainee readiness and safety outcomes (Wang et al. 2022b). These findings highlight the potential of immersive technologies to transform safety training in industrial settings.

2.1.5 VR safety training for supply chain and logistics

VR safety training has revolutionized the way organizations address frequent hazards in the workplace. By considering safety standards and procedures, VR training aims to prevent warehouse accidents and injuries. This innovative training method allows workers to identify and assess hazards, mitigate risks, respond to emergencies, handle materials and equipment safely, and ultimately reduce the severity and probability of risks. Cantor provides a comprehensive review of workplace safety in the supply chain, emphasizing the critical need for advanced training methods to improve safety outcomes (Cantor 2008).

Recent studies highlight the integration of VR training as a transformative tool for enhancing safety outcomes in logistics and supply chain operations. By utilizing immersive VR experiences aligned with learning theories, researchers have demonstrated significant improvements in operational safety, hazard identification, and risk assessment. For instance, de Juan-Ripoll et al. (2018) emphasizes VR's ability to enhance hazard recognition and compliance with safety standards through realistic, risk-free simulations. Similarly, case studies by Scorgie et al. (2024) in logistics companies show a notable reduction in accidents following VR implementation, while Hofstra et al. (2018) underscore its effectiveness in hazard identification and emergency preparedness in warehouse environments.

Further supporting this, Lewczuk and Żuchowicz (2024) advocate for VR integration as a tool to reduce accidents, promote proactive safety practices, and simulate complex hazard scenarios, ultimately improving decision-making processes. Additionally, Chatmon (2023) explores VR's role in enhancing warehouse safety management and fostering a stronger safety culture. Similarly, Verma et al. (2023) investigate VR's role in improving safety standards and operational efficiency in supply chain operations.

Moreover, Zhu and Li (2021) addresses the ability of VR and AR technologies to simulate complex scenarios, enhancing emergency response and decision-making. Overall, VR training offers faster learning, improved hazard recognition, and better safety practices by providing workers with realistic, hands-on experiences in a controlled environment. This makes VR an invaluable asset for enhancing safety and efficiency, particularly in supply chain and logistics operations.

2.2 Gap analysis

This section identifies specific gaps in the existing literature and justifies the need for research to highlight the novelty of the current study.

2.2.1 Identifying gaps

- **Lack of comprehensive VR safety training studies in warehouse environments:** The existing literature focuses mainly on general workplace safety or high-risk industries but lacks specific insights into warehouse environments (Cantor 2008; Maruchek et al. 2011; Hofstra et al. 2018).
- **Limited examination of VR's impact on risk assessment and safety auditing techniques:** While several studies have explored VR training for risk identification by hazard recognition, there is a scarcity of research on its effectiveness in assessing the risks and safety auditing techniques within warehouse environments (Chatmon 2023; Verma et al. 2023).
- **Insufficient mixed methods approach:** Most studies rely on either qualitative or quantitative approaches, with few employing a mixed methods design to provide a comprehensive understanding of VR safety training's procedures and its impact (Toyoda et al. 2022; Lewczuk and Żuchowicz 2024).
- **Need for specific VR features and training criteria assessment for Warehouse Safety:** There is a lack of research evaluating the importance of different VR features and training criteria based on expert opinions (Zhu and Li 2021; de Juan-Ripoll et al. 2018).

2.2.2 Justifying the need for research

- **Enhancing safety outcomes in warehouse environments:** Addressing specific gaps in warehouse safety training can lead to better safety outcomes, reducing accidents, injuries, and operational disruptions (Hofstra et al. 2018).
- **Improving safety auditing techniques:** Understanding VR's impact on safety auditing can help develop more effective auditing techniques, ensuring comprehensive risk management and safety compliance (Chatmon 2023).
- **Providing a comprehensive understanding of VR training:** Employing a mixed methods approach allows for a more holistic understanding of VR training's effectiveness, combining quantitative data with qualitative insights (Cantor 2008; Verma et al. 2023).
- **Identifying future improvements for VR systems:** Using the 9-window tool to analyze past, present, and future perspectives helps in identifying areas for improvement in VR safety training systems, enabling ongoing enhancement of the technology and its application in warehouse safety (Lewrick et al. 2018; Di Prinzio et al. 2021).
- **Assessing critical VR features:** Evaluating the importance of different VR features and training criteria optimizes VR safety training programs, enhancing their effectiveness and alignment with specific needs (Toyoda et al. 2022; Lewczuk and Żuchowicz 2024).

Organizations need to improve hazard recognition and foster a proactive safety culture utilizing the latest innovative tools, such as VR technology (Gauthier et al. 2022; Toyoda et al. 2022). This literature review highlights the transformative role of VR in enhancing safety training and auditing techniques within warehouse environments, where VR provides immersive and interactive learning experiences that lead to improved safety outcomes and operational efficiency (Scorgie et al. 2024; Bernabei et al. 2024).

However, there are gaps in the current literature, including a lack of comprehensive studies specifically focused on warehouse environments, limited examination of VR's impact on safety auditing techniques, and insufficient use of mixed methods approaches (Cantor 2008; Chatmon 2023; Verma et al. 2023). The review underscores the need for a comprehensive understanding of VR safety training through a mixed-methods approach to achieve a holistic evaluation of VR training's effectiveness (Toyoda et al. 2022; Lewczuk and Żuchowicz 2024).

The study's novelty lies in its focus on warehouse environments, exploration of VR's impact on safety auditing techniques, and evaluation of critical VR features and training criteria (de Juan-Ripoll et al. 2018; Zhu and Li 2021)

and identifies future improvements for VR systems. The review indicates that VR safety training enhances safety management, auditing skills, and risk management outcomes in warehouses.

3 Research methodology

This study employs a mixed-methods research design to evaluate the effectiveness of VR safety training in warehouses. Combining qualitative and quantitative approaches investigates VR in safety training and auditing techniques in warehouse environments presented in Table 1.

3.1 Research design

This research employs a four-stage methodology that includes observations (Robson et al. 2012), semi-structured interviews, in-depth discussions by critical thinking frameworks (Huitt 1998; Facione et al. 2016), and quantifying their decision using MCDM using AHP (Shringi et al. 2023; Bourhim and Cherkaoui 2020). This framework evaluates the adaptation processes of VR in safety training (Yoo et al. 2023; Scorgie et al. 2024) for the users and developers.

The study takes a comprehensive approach to improving the design and development of VR safety training. It combines workplace observations, engagement with workers and experts, and evaluations of current safety practices to identify gaps and understand existing protocols. Through in-depth interviews and critical thinking, the research explores how VR can enhance safety training. Furthermore, the AHP method prioritizes VR features based on their importance and impact, creating a detailed framework for integrating VR into warehouse safety practices.

Qualitative data from observations, semi-structured interviews, and critical thinking discussions were systematically triangulated with quantitative AHP results to validate the prioritization of VR features (Plano Clark 2017). This synthesis involved cross-referencing qualitative themes, such as identified training needs and user experiences, with AHP-derived feature rankings to ensure robust conclusions, enhancing the study's reliability through comprehensive data integration.

The study employed eight research questions, detailed in the introduction, to comprehensively explore the existing knowledge of VR safety training in warehouse environments. These questions were designed to address, step by step, critical aspects of utilizing VR in safety training and auditing in warehouse environments, including user training needs, workplace hazards, stakeholder perspectives, and implementation challenges, ensuring a thorough investigation of the research problem. Open-ended questions were utilized in Phases 1–3, observations, semi-structured

Table 1 Research design phases details

Phase	Sample	Questions	Methodology	Analysis
Phase 1: Observations	(5) Safety audit site visits	- What specific safety practices and hazards are prevalent in warehouse environments? - How are risk management strategies and safety audit procedures implemented to mitigate hazards in warehouse environments?	- Industrial workplace observations - Documenting and analyzing practices	Identify gaps and patterns in current practices and safety audit procedures, and explore how VR can address them
Phase 2: Semi-Structured Interviews	- 15 Safety Experts (Empathy map) - Delphi Technique with 10 experts (9 window tools)	- What are experts' perceptions regarding the effectiveness of VR training? (Empathy map) -How can VR be effectively integrated to address safety training needs? (Empathy map) - How do the current capabilities of VR safety training compare to systems and time? (9 window tool)	- Conduct interviews using: - Empathy map - 9-window tool	Using thematic analysis to explore training needs, VR integration, and user insights with empathy mapping and 9-window analysis
Phase 3: Questions Discussions	15 Safety Workers and Experts	- What are the key VR features necessary for effective safety training? - How do specific VR features contribute to improved safety training?	- In-depth discussions using CT questions	Using thematic analysis to evaluate VR features effectiveness and assess how it enhances safety skills and auditing techniques
Phase 4: AHP Analysis	10 Safety Experts	- Which VR features (e.g., simulation, risk identification, voice instructions, interaction, and navigation) are most effective in improving safety training?	- Apply AHP methodology - Pairwise comparisons to establish priorities	Calculate weights, consistency ratio, and aggregate results; rank the importance of VR features, and validate findings with AHP results

interviews, and critical thinking discussions to capture rich qualitative insights, aligning with the exploratory nature of the study (Plano Clark 2017). Open-ended questions allow experts to provide nuanced, context-specific insights into complex safety training needs that structured quantitative questions might overlook. Quantitative data, derived from the AHP analysis in Phase 4, complemented these findings by prioritizing VR features, balancing qualitative depth with quantitative rigor.

Ultimately, the study provides new initiatives to design immersive VR training systems that improve safety knowledge skills and abilities (KSAs) (Abich et al. 2021). These systems aim to create a safer and more efficient warehouse environment by addressing specific challenges and fostering a culture of innovation in safety practices.

3.1.1 Participant demographics

Experts were purposefully selected based on a minimum of 5 years of experience in safety management, with backgrounds in manufacturing clothing, food, construction, pharmaceuticals, biomedical, aviation, HSE, or vocational safety, ensuring diverse qualifications.

Tables 2 and 3 detail the number of participants, age, years of experience, and industry backgrounds, ensuring a clear context for the study's findings. Phase 1, Observations, involved site visits to five companies with no individual participants. Fifteen experts participated in the Empathy Map, as shown in Table 2, with a mean age of 38.3 years and a mean experience of 9.3 years, and the first ten of them

Table 2 Participant demographics for empathy map and 9-window tool phase

ID	Age (Years)	Exp. (Years)	Industry
1	31	8	Manufacturing - Clothing
2	33	9	Manufacturing - Food
3	32	10	Manufacturing - Clothing
4	43	8	Pharmaceuticals - Chemical
5	34	7	Pharmaceuticals - Chemical
6	30	5	Manufacturing - Clothing
7	45	14	Manufacturing - Clothing
8	27	5	Manufacturing - Food
9	48	10	Pharmaceuticals - Chemical
10	31	6	Pharmaceuticals - Chemical
11	41	5	Manufacturing - Construction
12	42	5	Manufacturing - Construction
13	38	8	Manufacturing - Construction
14	58	25	Manufacturing - Construction
15	37	15	Manufacturing - Construction

Note: All 15 participants were used for the Empathy Map; the first 10 (IDs 1–10) participated in the 9-Window Tool

Table 3 Participant demographics for critical thinking discussions and AHP phase

ID	Age (Years)	Exp. (Years)	Experience
1	43	11	Biomedical
2	51	12	Biomedical
3	54	10	Aviation
4	45	18	Aviation
5	32	8	Industrial - Construction
6	31	9	Industrial - Construction
7	48	18	HSE Specialist
8	33	8	HSE Specialist
9	57	20	HSE Specialist
10	38	11	HSE Specialist
11	52	13	Vocational Safety
12	32	9	Vocational Safety
13	31	5	Vocational Safety
14	28	5	Vocational Safety
15	41	24	Vocational Safety

Note: All 15 participants were used for Critical Thinking Discussions the first 10 (IDs 1–10) participated in the AHP Analysis

answered the 9-Window Tool with a mean age of 35.4 years and a mean experience of 8.2 years (Phase 2).

Table 3 shows a distinct group of 15 participants in Critical Thinking Discussions (Phase 3) with a mean age of 41.1 years and a mean experience of 11.8 years, with the first ten selected based on their expertise in decision-making methodologies for the AHP phase with a mean age of 43.2 years and a mean experience of 12.5 years (Phase 4), all from Jordan.

3.1.2 Observation phase

Observations include a detailed assessment of current safety practices and operational risks in the logistics sectors of pharmaceutical, clothing, and food companies. This research collects data from five safety audits to evaluate hazard occurrences and review auditing techniques, revealing critical aspects of workplace hazards and safety management. The assessment categorizes and addresses hazards in alignment with international standards such as OSHA (Occupational Safety and Health Administration) (Ko et al. 2010). It identifies the need for tailored safety standards, advanced monitoring systems, and ongoing employee training to mitigate risks effectively. Finally, the observations uncover gaps in practices and highlight areas for improvement in warehouse safety training.

This phase involved site visits to five companies located in the Al Hasan Industrial Estate, Irbid, Jordan, a major industrial hub hosting 136 companies with a total of 30,163 workers (Jordan Industrial Estates Company 2023). These

companies were purposefully selected to represent diverse industry types, including textiles and apparel manufacturing, food processing, and chemicals & fertilizers, to capture a range of workplace hazards relevant to VR safety training in the industrial context. Table 4 summarizes the industry type, size, and a brief description of each company.

3.1.3 Semi-structured interviews phase

Semi-structured interviews with 15 safety experts are conducted to develop an empathy map, exploring VR integration in safety training. A second interview, following the Delphi method with 10 experts, examines the 9-Window framework to assess VR safety training's current capabilities across systems and time. This approach provides in-depth insights into the benefits and challenges of VR-based safety training.

Empathy map

An empathy map is a framework that explores users' perspectives, behaviors, and emotions (Köppen et al. 2011; Pileggi 2021; Gray 2010), typically organized into four quadrants: Says, Thinks, Does, and Feels, in addition to Pains and Gains. These categories effectively summarize user experiences and perceptions about VR training. Says captures direct feedback or verbalized thoughts, while Thinks focuses on internal beliefs or considerations about VR training. Does highlight actions or practical experiences during training and feels reflect emotional responses and engagement levels. Furthermore, Pains identifies challenges or obstacles faced during or related to VR training, while Gains outlines the benefits and positive outcomes derived from using VR training. To fill the empathy map,

interviews explore participants' experiences, perceptions, and challenges with VR-based safety training after viewing different VR safety applications using Oculus Quest 2 and 3. Each question aligns with the empathy map categories to ensure a comprehensive understanding of the trainee experience, as shown in Table 5. The interview questions were reviewed by field experts in VR training and safety management to ensure content validity, relevance to industrial safety scenarios, and alignment. By addressing initial reactions, practical engagement, emotional responses, challenges, and the perceived value of the training, these questions aim to identify key areas for improvement and ensure that the training program meets user needs effectively while improving safety preparedness.

Creating an empathy map for VR safety training users provides essential insights into their experience. Starting with the Says quadrant captures their initial reaction of both excitement and hesitation about VR-based training. They often inquire about how applicable the training is to actual scenarios, reflecting concerns about the training's practical value. Feedback during and after sessions frequently includes both positive impressions and areas where improvements could enhance the experience.

In the Thinks quadrant, trainees contemplate whether VR training effectively builds skills and knowledge. They question how well they are performing, wonder if VR training improves practical abilities, and consider how employers and the industry regard VR-based training. These thoughts highlight a mix of curiosity and uncertainty as they seek confirmation of VR's professional value.

The Does quadrant reflects experts' practical engagement with VR. They participate in simulated safety

Table 4 Companies involved in observation phase

ID	Industry type	Size (workers)	Brief description
1	Textiles & Apparel	3000–4000	Manufactures various textile and apparel products
2	Textiles & Apparel	1500–2000	Manufactures various textile and apparel products
3	Food Processing	400–500	Specializes in food processing and packaged food products
4	Chemicals & Fertilizers	151–200	Major producer of pesticides and veterinary medicines
5	Chemicals & Fertilizers	51–100	Major producer of pesticides and veterinary medicines

Table 5 Interview questions based on empathy map categories

Category	Questions
Says	What were your first thoughts about using VR for training? What feedback did you share during/after training?
Thinks	How relevant do you think VR training is to real-world safety? Do you think VR training builds skills better than traditional methods?
Does	What practical tasks in VR training were the most engaging or challenging? What gaps did you notice in the VR training that affected your ability to apply skills?
Feels	How did your emotions change during the VR training? How did adapting to the VR training environment affect your experience?
Pains	What challenges did you face using the VR equipment? Did anything about the training make it difficult?
Gains	What benefits did you gain from using the VR equipment? How has VR training improved your readiness for safety tasks?

scenarios, practicing skills such as hazard identification and corrective actions. Repetitive hands-on sessions allow users to reinforce these skills, which helps bridge the gap between virtual training and real-world applications.

The Feels quadrant indicates experts' emotions. Users may feel anxious at the beginning, but they raise confidence when they become accustomed to the VR environment as a new technology. The immersive nature of VR leads to high emotional responses with more tangible and effective training. Positive reinforcements reinforce the user's sense of achievement.

To understand the challenges and benefits, the empathy map was extended to include both pains and gains. On the pains, this study investigates the VR challenges such as discomfort, technical difficulties, fear of making mistakes, and anxiety about how realistic the VR training is. Addressing these concerns ensures that VR training is designed to meet diverse learning needs effectively.

Lastly, gains include VR training benefits such as achieving goals, enhancing safety knowledge, improving readiness, and building confidence for real-world situations. Users gain recognition for their newly acquired skills, while diverse training scenarios create an effective learning environment.

This comprehensive empathy map provides a detailed view of VR trainees' experiences, thoughts, feelings, and behaviors. Therefore, guide VR design and developers of the safety training program to meet the trainees' needs and deliver an effective learning experience.

9 Window Tool

TRIZ's 9-Window Tool is an analytical framework that examines systems across three levels: subsystem, system, and supersystem, and three-time frames: past, present, and future. This approach, often referred to as the 9-box method, provides a holistic perspective on problem-solving and innovation by exploring how systems evolve and interact over time (Terninko et al. 1998; Kyeongwon 2015; Lewrick et al. 2018).

To develop the 9-Window, the Delphi Technique was employed, engaging 10 safety experts to create a 3x3 matrix. The top row analyzes the past, focusing on historical context and system origins. The middle row evaluates the present, detailing current features and practices, while the bottom row anticipates future advancements, particularly in response to rapid technological changes. The tool has been widely applied, from simplifying problem-solving frameworks for middle and high school students by integrating design thinking and TRIZ (Kyeongwon 2017) to structuring innovative solutions in digital transformation initiatives for complex ecosystems (Lewrick et al. 2018).

For a VR safety training application, this analysis would look as follows:

- **Subsystems:** The components that support the VR system, such as VR headsets and controllers.
- **System:** The main element is VR-based training sessions.
- **Supersystem:** The larger environment, such as industry regulations and evolving safety standards that interact with the training system.

This structured approach provides a comprehensive understanding of the system and facilitates targeted improvements at different levels, enabling effective innovation and problem-solving strategies.

3.1.4 Critical thinking discussions: in-depth discussion phase

Further interview sessions incorporate critical thinking methodology, a key element of effective investigation processes. This approach emphasizes evaluating the impact of VR applications, particularly in safety training, ensuring a thorough and analytical assessment. Since Greek philosophers, critical thinking has been valued as a higher-level cognitive skill, with its ability to critique subjects from various aspects, making it an essential educational focus (Huit 1998; Facione et al. 2016; Potter 2022). As a result, this study extends beyond merely gathering user feedback.

The CT interview framework involves a variety of details, including observing features, analyzing functionalities, interpreting personal experiences, inferring strengths and weaknesses, and judging the overall effectiveness of the VR training (Barak and Shahab 2023). In addition to that, the framework encourages the exploration of VR features and their impact on safety outcomes along with other solutions, improvements, and decisions regarding effective training. This comprehensive approach provides valuable insights and multi-faceted feedback that can be used to refine the VR application and assess its impact on safety training outcomes.

As a result, interviews were conducted with 15 experts using semi-structured interview questions with a critical thinking approach. To ensure a comprehensive and iterative development process throughout all aspects of designing, implementing, and evaluating the VR application utilization for safety training in warehouses, an interview questions guide was developed to evaluate the VR application using critical thinking components of trainees' experiences with VR safety training.

CT discussion interview involves a set of components (Facione et al. 2016; Potter 2022). Although the exact breakdown might differ slightly depending on the source, these components translate into a set of questions for the interview.

- **Observing:** Focuses on the VR environment itself by describing a safety situation in a warehouse. Where the trainee can observe and gather information in VR safety training.
- **Analyzing:** Assessing the safety of a VR warehouse environment by systematically and thoroughly reviewing the data in VR safety training. How does the VR environment help you assess safety risks?
- **Interpreting:** Focuses on understanding and explaining the meaning of the information in VR safety training, drawing conclusions, and explaining the importance of safety standards.
- **Inferring:** Evaluating the link and finding helpful aspects of VR safety training by drawing analytical reasoning based on the information available in VR safety training.
- **Judging (Evaluation):** Focuses on evaluating information and making informed decisions. Prioritizing safety tasks by making logical and informed decisions and evaluations in VR safety training.

In addition to that, this research asks further questions regarding the continued improvement process as follows:

- **Creating:** Suggesting changes and improvements for the future implementation of VR safety training.
- **Deciding:** Making decisions about the effectiveness of the VR safety training and taking actions accordingly.

Overall, CT is a multifaceted skill involving various components working together to enable individuals to think rationally and independently about information and decisions.

3.1.5 AHP analysis phase

The final phase applies the AHP, multi-criteria decision-making (MCDM) tool (Shringi et al. 2023; Bourhim and Cherkaoui 2020), to systematically prioritize and rank VR features based on expert opinions. AHP was selected to prioritize VR safety training features due to its suitability for handling subjective expert judgments in a hierarchical decision-making framework, making it more appropriate than other MCDM models, such as Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), which emphasizes distance to an ideal solution but may be less effective with interdependent criteria (Lai et al. 1994; Behzadian et al. 2012), or Simple Additive Weighting (SAW), which relies on straightforward additive scoring and may not capture complex trade-offs (Afshari et al. 2010; Kaliszewski and Podkopaev 2016). AHP's pairwise comparison method enabled the first 10 experts in Table 3 to systematically evaluate the relative importance of features like simulation realism and interactivity, aligning with the complex, safety-critical context of warehouse environments.

Its structured approach ensured robust integration with qualitative findings from Phases 1 to 3 (Plano Clark 2017), providing clear prioritization for VR implementation.

This phase begins by defining a hierarchical structure in which the primary goal is to identify the most effective VR features for safety training to allocate resources accordingly. Prioritizing VR features assesses users' and developers preparedness to maximize the VR-based training solutions implementation.

The VR features criteria, derived from earlier phases, include the following factors:

- **Simulation Realism:** The ability to replicate real-world hazards and scenarios.
- **Risk Identification:** Effectiveness in helping trainees recognize potential risks.
- **Interaction:** The level of immersive and hands-on involvement provided.
- **Voice Guidance:** The quality and effectiveness of verbal instructions provided within the VR environment.
- **Navigation:** The simplicity and intuition with which learners move and maneuver inside the simulated environment.

To ensure feature evaluation, experts fill out the AHP pairwise comparisons form, assessing the relative importance of each criterion. A scale of 1 to 9 is utilized for these comparisons, where 1 represents equal importance and 9 represents extreme importance. To validate the consistency of the expert judgments, a consistency ratio (CR) is calculated. A CR value below 0.1 is considered acceptable, ensuring reliability in the ranking process. Following this, the priority weights of the criteria are computed, leading to the final ranking of VR features based on their effectiveness in safety training scenarios.

AHP analysis method

Pairwise comparison matrix For each criterion, pairwise comparisons were constructed using expert input. For example, if experts rated "Risk Identification" as significantly more important than "Navigation," a value of 7 might be assigned in the matrix. The comparisons for all criteria were recorded in a square matrix.

Priority weights The pairwise matrix was normalized by dividing each element by the sum of its column. The average of each row was then calculated to determine the weight of each criterion.

Consistency check The consistency index (CI) was calculated using the formula:

$$CI = \frac{\lambda_{\max} - n}{n - 1}$$

where $\lambda_{\max}$ is the principal eigenvalue, and n is the number of criteria. The consistency ratio (CR) was then computed by dividing the CI by the random index (RI) for the corresponding n . The CR value less than 0.1 validated the consistency:

$$CR = \frac{CI}{RI}$$

A CR value below 0.1 indicates that the expert judgments were consistent.

Aggregation of results The final priority weights of VR features were aggregated and ranked based on their values. The aggregation of the results from ten experts provided the final rankings for the VR features, ensuring a consensus-based decision-making process. Data were analyzed using Excel as a software tool to ensure precision in AHP calculations. The results of this phase emphasize the critical importance of VR features to enhance the overall effectiveness of safety training.

Finally, this methodology integrates qualitative and quantitative approaches that include the combination of observational analysis, expert input, critical thinking discussions, and AHP, ensuring a comprehensive assessment that addresses the research questions systematically. The findings contribute to the development of VR-based safety training solutions tailored to the needs of warehouse environments.

4 Result and discussion

4.1 Observation

4.1.1 RQ 1: What specific safety practices and hazards are prevalent in warehouse environments?

Observations result from five industrial companies' visits that analyze workplace hazards identified during the assessment and review safety audits and can be classified into different types to address them. Table 6 summarized the workplace hazards. Below is a breakdown of these hazard categories, focusing on how they align with safety standards.

Physical hazards are among the most common in workplaces, especially in this kind of industry. These hazards include noise exposure (e.g., loud machinery for long hours), lighting both insufficient and excessive, heat, especially in high-temperature environments, and vibration from heavy equipment or tools. A critical concern is the risk of slips and trips on slippery surfaces leading to falls, tripping incidents, or accidents caused by falling objects or uneven ground. Confined spaces limit mobility and lead to oxygen deficiency or other risk conditions. Additionally, manual handling and overhead cranes required regular maintenance to avoid physical risk.

Chemical hazards also include liquid, gaseous, and solid chemicals that cause harm through inhalation, skin contact, or accidental ingestion. To prevent these hazards, it

Table 6 Observation results: workplace hazards

Hazard category	Observation findings
Physical Hazards	Noise exposure from loud machinery, insufficient/excessive lighting, heat (especially near machinery), vibration from heavy equipment, slips/trips/falls (slippery surfaces, uneven ground, falling objects), confined spaces, manual handling, overhead cranes
Chemical Hazards	Liquid, gaseous, and solid chemicals; improper storage/labeling; inadequate ventilation; chemical waste management
Mechanical Hazards	Hazards associated with ladders, scaffolding, and floor conditions; lack of railings; unsafe material handling practices with moving machinery
Electrical Hazards	Contact with live wires, malfunctioning equipment, untagged switches, faulty installations; lack of fire extinguishers and alarms
Biological Hazards	Exposure to flying insects; water contamination
Ergonomic Hazards	Improper use of chairs/tables; inadequate work platforms; excessive strain from workstation use
Fire and Emergency Hazards	Lack of/inaccessible fire extinguishers and alarms; outdated emergency plan; inadequate training; unmarked exits; lack of assembly points; insufficient water resources for fire control
Storage Hazards	Improper material segregation; heavy items stored at height; insufficient clearance; failure to meet setback requirements; lack of containment systems; inadequate storage audits
Human Factor Hazards	Actions due to curiosity, negligence, or recklessness; influenced by worker characteristics (age, experience); inadequate training; lack of a safety culture
Health and First-Aid Hazards	Inadequate first aid kits; lack of trained medical personnel; absence of regular medical examinations
Miscellaneous Hazards	Lack of safety audits and hazard reporting; poor hygiene in food service areas; risk of being struck by moving vehicles (inadequate traffic control, untrained drivers, lack of pedestrian walkways, blind spots, speed limits, vehicle maintenance)

is critical to store and label chemicals properly. Additionally, wearing appropriate face masks, gloves, and protective clothing, along with maintaining effective workplace ventilation, helps minimize risks. Furthermore, manage chemical waste according to the material safety data sheet (MSDS) instructions to prevent environmental contamination and protect workers from exposure to harmful substances.

Mechanical hazards are a major concern in environments where machinery and equipment are in operation. Risks linked to ladders, scaffolding, and the condition of flooring have a high probability of severe injuries. Additionally, follow correct material handling practices and intensive safety awareness with warning posters to minimize risks associated with moving machinery.

Electrical hazards include contact with live wires, faulty or malfunctioning equipment, untagged switches, or improper location, which has a high probability of electric shocks. To reduce these risks, it is essential to have regular maintenance for the electrical components and facility management planning.

Biological hazards involve exposure to harmful biological agents, such as disease-carrying insects or contaminated water, which have a high probability of causing significant health problems. Proper precautions and preventive measures are necessary to minimize these risks and protect individuals from potential harm. Ensuring proper hygiene, sanitation, and pest control measures are essential in controlling biological hazards.

Ergonomic hazards are the result of poorly designed workspaces that can lead to musculoskeletal injuries. For example, improper use of chairs and tables, inadequate work platforms, and excessive strain from workstation use cause long-term health issues, such as repetitive strain injuries or chronic back pain.

Fire and emergency hazards are a constant concern in the workplace. To avoid that, ensure that fire extinguishers and fire alarm systems are accessible and operational. In addition, having an up-to-date emergency plan and consistently training all workers on the plan and their designated roles during an emergency are crucial for workplace safety. Additionally, well-marked emergency exits and designated assembly points allow for a safe and efficient evacuation in case of an emergency. Wells and pumps are also crucial resources for fire control, particularly in industrial environments.

Proper storage practices are essential to prevent accidents and damage within a facility. Materials should be segregated into appropriate categories to prevent incompatible substances from reacting. Heavy equipment and materials should be stored on lower shelves, while lighter items should be placed on higher shelves to minimize the risk of injuries from falling objects and facilitate easier access. Maintain proper clearance between shelves and above-stored materials

to allow proper ventilation and easy access and prevent accidental dislodgement. Setback requirements must be adhered to, ensuring sufficient distance between storage areas and building boundaries to prevent hazards in case of fire or spills. Containment systems, such as drip trays or containment basins, should be utilized to prevent spills of hazardous materials to the environment. Finally, conduct regular internal storage audits to identify hazards such as damaged containers, blocked aisles, or expired materials.

Human factor hazards result arise from curiosity, negligence, or recklessness, influenced by worker characteristics like age and experience. Proper training is essential to ensure employees consistently understand and follow safety procedures. These findings highlight the need to cultivate a safety-focused culture, reducing errors caused by human behavior.

Health and first-aid hazards involve ensuring that workplaces are equipped to handle health emergencies. Adequate first aid kits, trained medical personnel, and regular medical examinations are necessary to maintain a healthy and safe workforce.

Other miscellaneous hazards require careful attention. Regular safety audits, coupled with comprehensive hazard reporting and management records, are crucial for proactive risk identification and mitigation. In food service areas, such as restaurants and employee break rooms, maintaining high standards of hygiene is paramount to preventing illnesses and maintaining a healthy work environment. Furthermore, the risk of being struck by moving vehicles, particularly in industrial areas and storage facilities, demands significant attention. To mitigate this risk, it is essential to implement traffic control measures such as marking designated vehicles and pedestrian pathways within the facility and storage areas using appropriate signage and ground markings. Only licensed and properly trained drivers should be permitted to operate vehicles within the facility. Safe crossing points for pedestrians should be designated and marked. Mirrors should be installed in blind spots to improve visibility for both drivers and pedestrians. Appropriate speed limits should be established and enforced for vehicles within the facility. Regular vehicle maintenance, with a particular focus on brake inspections and maintenance, is crucial to ensure safe vehicle operation. Finally, ongoing driver training should be provided to all drivers, emphasizing safe driving practices within the facility, including defensive driving techniques and awareness of pedestrians. By addressing these miscellaneous hazards, industries can significantly enhance workplace safety and minimize the risk of accidents.

Addressing these diverse hazard categories is essential for creating a safe workplace. Following OSHA (Ko et al. 2010) and international safety standards ensure that workers are protected from all hazard types. Implementing proper regular training and continuous monitoring of workplace

conditions are key steps in reducing risks and preventing accidents.

4.1.2 RQ 2: How are risk management strategies and safety audit procedures implemented to mitigate hazards in warehouse environments?

The observations revealed that while some companies had implemented risk management strategies and safety audit procedures, significant gaps persisted in their effectiveness. For example, safety audits identified inadequate work procedures, unsafe acts, and unsafe behaviors among employees, all of which contribute to workplace hazards. These gaps highlight that current risk management strategies and safety training are insufficient to fully mitigate risks. Using a deductive approach, these findings were evaluated against established safety standards, such as the ISO 45001 safety management system and its benefits (Malinda and Soediantono 2022; Karanikas et al. 2022), which emphasizes proactive hazard identification and continuous improvement through comprehensive safety training. The evaluation emphasized the necessity for robust, adaptive, and systematic safety audit procedures and worker training to enhance risk management practices.

Current safety training programs fall short of addressing the dynamic and complex challenges of modern workplaces, as conventional methods lack flexibility and fail to engage employees effectively. This highlights the need for innovative solutions, such as VR safety training, which offers immersive simulations of real warehouse hazards. By engaging employees in dynamic, realistic scenarios, VR provides hands-on experience, identifies gaps in safety practices, and fosters a safer, more efficient workplace.

For safety auditors, VR enhances evaluation processes by immersing them in virtual environments that replicate complex operations. This allows auditors to practice identifying hazards, assessing unsafe conditions, and evaluating safety procedures without physical risks. Customized VR scenarios tailored to specific industries improve training precision, while collaborative virtual simulations enable multiple auditors to work together, promoting a unified approach to safety audits. Ultimately, VR training strengthens safety management systems, improves audit quality, and creates safer work environments.

4.2 Semi-structured interview

The qualitative data gathered from semi-structured interviews with 15 VR safety experts were used to complete the empathy map, while data from the Delphi technique (Powell 2003) were applied to fill the 9-window tool from 15 experts, resulting in actionable and implementable findings. Participants reported a high appreciation for the interactive

nature of VR-based training, with notable improvements in confidence and safety knowledge. However, concerns about technical barriers and the practical transfer of VR-acquired skills to real-world scenarios were frequently noted. These findings highlight the dual challenge of enhancing the technological robustness of VR systems while ensuring seamless integration into workplace safety standards. Such insights are critical for tailoring VR training tools to industry-specific needs and maximizing their effectiveness in reducing workplace hazards.

4.2.1 Empathy map

The qualitative analysis of empathy map responses summarized in Table 7 contributed valuable insights from participants' experiences.

Answering RQ 3: What are experts' perceptions regarding the effectiveness of VR training?

Experts' perceptions of the effectiveness of VR training reveal a positive perspective, with numerous benefits highlighted in various categories as the following:

Says: Initial Reactions & Feedback: 80% of participants said they appreciated the novelty, excitement, and immersive nature of VR, with 73.33% expressing positive initial responses and enthusiasm for the new technology. 66.67% mentioned that they found the interactive and engaging learning format enjoyable. However, 60% of participants said they had concerns about the practical application of VR-acquired skills in real-world scenarios.

Think: Perceived Relevance & Effectiveness: 86.67% of participants thought VR training was effective, accessible, and realistic, with 80% agreeing on its relevance to real-world safety. Additionally, 80% of participants thought VR could replace traditional training methods, and 73.33% noted its positive impact on cognitive and interpersonal skills. Despite these positive outcomes, 53.33% thought that skill transferability and employer recognition of VR training might be an issue.

Does: Practical Tasks & Identified Gaps: 86.67% of participants found VR simulations engaging and realistic, and 80% emphasized the value of risk-free experimentation. However, 66.67% noticed that there were gaps in VR technology adoption and support, indicating that improvements in these areas were necessary.

Feels: Emotional Journey & Adaptation: 80% of participants felt increased confidence and reduced anxiety during VR training, while 73.33% described a positive emotional response to the immersive experience. However, 60% felt frustrated with VR controls, highlighting the need for improvements in user experience.

Pains: Challenges Faced: 73.33% of participants mentioned facing barriers, including concerns about the cost, availability, and integration of VR training. 60% reported

Table 7 Summary of key points and percentages of qualitative results from participants

No.	Key points	Percentage
1	Says: Initial Reactions & Feedback	
	Novelty, Excitement, Engagement, Immersive Experience, 3D Models	80%
	Positive initial response, enthusiasm for new technology	73.33%
	Appreciated interactive and engaging learning	66.67%
	Concerns about practical application in real-world scenarios	60%
2	Think: Perceived Relevance & Effectiveness	
	Effectiveness, Efficiency, Accessibility, Realism, Skill Development	86.67%
	High perceived relevance for real-world safety	80%
	Ability to replace traditional training methods	80%
	Positive impact on cognitive and interpersonal skills	73.33%
	Concerns about skill transferability and employer recognition	53.33%
3	Does: Practical Tasks & Identified Gaps	
	Engagement, Realism, Application, Limitations, Support	86.67%
	Found VR simulations engaging and realistic	80%
	Highlighted the value of risk-free experimentation	73.33%
	Identified gaps in VR technology adoption and support	66.67%
4	Feels: Emotional Journey & Adaptation	
	Confidence, Anxiety Reduction, Engagement, Frustration	80%
	Increased confidence and reduced anxiety	73.33%
	Positive emotional response to immersive experience	66.67%
	Minor frustrations with VR controls	60%
5	Pains: Challenges Faced	
	Limited awareness and understanding of VR benefits	73.33%
	Barriers, Limitations, Accessibility	73.33%
	Concerns about cost, availability, and integration	66.67%
	Technical issues and equipment limitations	60%
6	Gains: Benefits & Readiness Improvements	
	Skill Development, Risk Reduction, Flexibility	86.67%
	Enhanced safety knowledge and improved decision-making	80%
	Increased confidence and readiness for safety tasks	80%
	Cost-effective and motivated training solution	75%

encountering technical glitches and equipment limitations during the training. Additionally, 73.33% felt there was limited awareness and understanding of the benefits of VR training, presenting a significant challenge.

Gains: Benefits & Readiness Improvements: 86.67% of participants gained significant benefits in terms of skill development and risk reduction, and 80% reported enhanced safety knowledge and improved decision-making skills. Furthermore, 80% felt more confident and ready for safety tasks. 75% considered VR training a cost-effective and flexible solution for their learning needs.

Answering RQ 4: How can VR be effectively integrated to address safety training needs?

VR can be effectively integrated into safety training by focusing on its immersive and interactive features that motivate participants and improve real-world safety skills (Tusher et al. 2024; Stefan et al. 2023). Experts highlighted the importance of customizing VR scenarios that address

specific safety challenges in various industries. To optimize integration, VR training should be adaptable, with comprehensive support systems in place to address technical issues and ensure smooth execution. Additionally, overcoming barriers such as readiness and adaptability, along with improving VR controls to minimize user frustrations, enhances its effectiveness. Ultimately, integrating VR effectively requires a focus on VR features that enhance the training procedures to address diverse safety needs.

The Empathy Map results are supported by qualitative data collected from the experts during Phase 2 semi-structured interviews. These experts, representing diverse industries, provided detailed responses on workers' safety training needs, perceived challenges in current practices. Their insights were systematically analyzed to construct the Empathy Map, identifying key user needs and barriers to effective safety training. These findings were triangulated with observations from the five companies visited in Phase

1. This triangulation, following established mixed-methods approaches (Plano Clark 2017), ensured the robustness of the results by cross-referencing expert insights with actual workplace hazards, enhancing the clarity and reliability of the Empathy Map outcomes.

In summary, these findings underscore VR as an effective training tool, although there are areas for improvement, including better technology support, improved consumptive realism in scenarios, and addressing VR features to avoid adaptation challenges.

4.2.2 9 Window tool

Answering RQ 5: How do the current capabilities of VR safety training compare to systems and time?

9 Window Tool provided clear insights into both the current impact and future methods of VR safety training. It became evident that VR technological enhancements have transformed traditional training into an immersive, adaptable, and comprehensive process. Key hardware and software

components allow trainees to engage deeply in scenarios that replicate real-world hazards, improving retention, confidence, and response accuracy. Moreover, by structuring training steps such as hazard identification, assessment, and mitigation, the VR system has developed into an effective safety learning ecosystem. Furthermore, the 9-Window Tool supported the design of a robust VR safety training application and provided a roadmap for continuous improvement, aligned with evolving technological capabilities and industry requirements. This dual-method approach enabled a comprehensive view of both present benefits and future methods, solidifying VR training's role in advancing workplace safety practices.

Using the 9-Window Tool as summarized in Table 8, this research identified significant insights into the evolution of VR safety training systems. The study revealed a shift from traditional methods reliant on manuals and basic drills to present-day practices featuring immersive VR simulations supported by advanced technologies like haptic feedback and real-time analytics. Future projections indicate a trend

Table 8 Evolution of safety training across time and dimensions 9 window

Time/dimension	Subsystems	System	Supersystem
Past	Traditional safety manuals and early digital simulations	In-person safety training with minimal VR integration	Initial safety regulations and compliance focus
	Basic hands-on safety drills	Early prototypes of basic simulations	Early workplace safety standards incorporating digital tools
	Limited assessment tools for measuring safety knowledge	Static and repetitive safety scenarios	Focus on one-size-fits-all safety protocols
	Reliance on instructor-led demonstrations without technology		
Present	Advanced VR hardware with high-res displays, 6DOF, spatial audio, and controllers	VR-based safety training with interactive and realistic scenarios	Industry standards now recommend VR as a training method
	Haptic feedback for immersive learning	Trainees practice risk assessment and mitigation	Increased awareness of the importance of personalization in training
	Real-time analytics for monitoring trainee performance	Integration of multi-sensory feedback (audio, visual, haptic)	Emphasis on measurable outcomes for regulatory compliance
	Cloud-based storage for training data	Collaboration features for group-based safety training in VR	Industry-wide competitions for innovative VR safety solutions
	Modular VR training content for various industries		
Future	Next-gen haptic suits for full-body feedback	Highly immersive, integrated, and adaptive VR training	Broad VR adoption setting new industry standards
	AI-driven scenarios tailored to trainee skill levels	Scenarios ranging from routine to emergency responses	Enhanced safety protocols derived from VR training insights
	Real-time hazard detection sensors	Mixed-reality training combining VR and real-world elements	Dynamic regulatory frameworks integrating AI and VR capabilities
	Brain-computer interfaces (BCI) for tracking trainee mental states and controlling during training	Autonomous VR systems with predictive learning capabilities	Global standards for VR safety certifications and benchmarking
	Virtual collaboration across global teams for sharing best safety practices	Training focused on addressing mental health and safety under high-stress scenarios	Proactive safety culture where VR tools identify and mitigate risks before they arise

toward highly adaptive, AI-driven training environments integrated with real-world scenarios and global safety standards. This structured analysis provides a comprehensive framework for understanding and advancing VR-based safety training to meet evolving industry needs and regulatory expectations.

4.3 Critical thinking discussions

Answering RQ 6: What are the key VR features necessary for effective safety training?

The critical thinking interview allowed experts to highlight VR features used for designing and evaluating the effectiveness of a safety training simulation within a VR application. This analysis explores interview responses gathered through the CT framework as shown in Appendix A to evaluate a VR application designed for warehouse safety training. Additionally, results provide comprehensive details about both the strengths and limitations of the VR training method. VR simulation and misplaced items were integrated, as both have the key component of VR simulation content.

VR features were summarized as the following:

Simulation of misplaced items: Being accustomed to the VR warehouse environment is an essential concept. Because of its familiarity, it provides trainees with an engaging experience while effectively preparing them for the variety of layouts that exist in actual warehouses. This emphasizes the importance of maintaining accuracy. In VR workplace simulation, safety training motivates trainees to investigate the arrangements of items and recognize risks resulting from illogical arrangements by adding scenarios that test trainees' ability to locate misplaced items. A further advantage was the development of spatial reasoning abilities that enable trainees to mentally map their surroundings, which is considered an essential skill for navigating in actual warehouses. The trainees were asked to interpret visual cues to understand object properties and their placement within the virtual environment. The analysis demonstrates the importance of incorporating misplaced items into VR training, including scenarios with misplaced items that improve the training's effectiveness and encourage trainees to observe their surroundings, which is considered a fundamental skill for risk identification.

Risk identification: The results indicate that VR appears to be a useful tool for risk identification based on visual cues. This necessitates the expansion of training to cover a wider range of risks, including those that are not immediately apparent from visual cues alone. Furthermore, as the interview responses indicate, VR training has an opportunity to develop multisensory awareness by encouraging trainees to pay attention to cues in addition to visual cues, such as

haptic cues, which result in a more comprehensive understanding of the identification of risks.

Voice instructions: Another important finding is clear for trainee awareness: VR training can effectively improve trainee comprehension of safety procedures and the utilization of voice instructions. Additionally, other experiments were required with various voice instruction techniques to enhance trainees' learning processes.

VR interaction: provides trainees with the opportunity to practice appropriate handling techniques in a safe and controlled environment. Additionally, exploring different VR control methods enhances the user experience by making it more natural and user-friendly for trainees to interact with objects within the VR environment. These interactions are well-designed to facilitate the transfer of learned skills from the VR environment to actual scenarios.

VR navigation: The navigational aspect of VR training was concluded by the analysis. While controller-based navigation provides increased accessibility for a wider range of users, it might also lead to disorientation and motion sickness for some users. This emphasizes the need for exploring alternative navigation methods that are both intuitive and comfortable for users, such as teleportation. Also, VR navigation itself contributes to the development of spatial reasoning skills by requiring trainees to mentally map the virtual environment as they navigate through it.

VR safety training has an opportunity to improve warehouse safety. Trainee interviews provided new approaches for future development. Participants emphasized the importance of including industry-specific details, such as materials and equipment, to develop a more effective training experience. It was additionally suggested that an actual risk scenario be included. The interview discussion implies that the VR application is considered a new safety training method and indicates that VR has a positive reaction with users and also provides a creative method for enhancing safety awareness and practical skills through VR safety training. Further research is required to comprehend user behavior in warehouses in the short and long term. Finally, apply the safety principles of VR warehouse training to other fields with similar risks.

Answering RQ 7: How do specific VR features contribute to improved safety training?

Specific VR features contribute to improved safety training by enhancing key learning processes. Simulation of misplaced items allows trainees to identify and address risks, improving spatial awareness. Risk identification in immersive scenarios fosters hazard recognition and decision-making skills. Voice instructions enhance comprehension and retention of safety protocols through multisensory learning. VR interaction enables the practice of handling techniques, improving skill proficiency. Finally, VR navigation helps trainees develop spatial reasoning and

effective responses to real-world situations. Collectively, these features support cognitive and spatial learning, ensuring more effective actual safety training applications.

4.4 AHP

Answering RQ 8: Which VR features (e.g., simulation of misplaced items, risk identification, voice instructions, interaction, and navigation) are most effective in improving safety training?

The AHP analysis identified the most critical VR features for effective safety training in warehouse environments through the questionnaire in Appendix B. The results revealed that simulation realism (28%) is the most influential feature, followed closely by immersive interaction (23%).

These features significantly enhance trainees' ability to engage actively with the training environment. The total percentages are (100%). Risk Identification (21%) ranked third, underscoring the importance of replicating actual scenarios. Meanwhile, voice guidance (11%) and navigation (14%) were deemed less critical but still relevant for improving training outcomes. The detailed prioritization of VR features is summarized in Table 9.

AHP methodology ensured a rigorous and consistent evaluation of expert judgments, leading to reliable results. Therefore, the consistency ratio (CR) for all pairwise comparisons was 0.01076, which is below the acceptable threshold of 0.1, confirming the consistency of the evaluations and the reliability of the expert judgments.

The result shows that simulation realism, immersive interaction, and risk identification are the most critical VR features for effective safety training, contributing to knowledge recognition and skill development. These findings emphasize the importance of integrating advanced VR features with complementary training methods to improve safety outcomes in warehouse environments.

Table 9 Prioritization of VR features for safety training

VR feature	Priority weight (%)
Simulation Realism	28%
Immersive Interaction	23%
Risk Identification	21%
Navigation	14%
Voice Guidance	11%

5 Research contribution

Theoretical Contributions: This study focuses on under-researched areas and developing frameworks for VR training, utilizing observations, empathy mapping, the 9-window tool, critical thinking discussions, and AHP to ground its findings.

- **Focus on warehouse environments:** This research, informed by observations of warehouse hazards examines the unique safety challenges in different industries, contributing to a deeper understanding of this important area (Hofstra et al. 2018; Cantor 2008; Verma et al. 2023). This contributes by providing a theoretical basis for targeted safety interventions in warehouses.
- **Impact on safety auditing techniques:** The study explores VR's role in enhancing safety auditing techniques, providing insights into the evolution of safety management systems. Using tools like the 9-window method and critical thinking discussions, the research explores the VR utilization in improving hazard identification and risk assessment (Tompkins et al. 2010; Atkin and Brooks 2021; Roper and Payant 2014). This contributes by linking VR features and audit techniques.
- **Assessment of VR features and training criteria:** The research develops a theoretical framework for VR training by assessing key features and criteria. Through AHP, the study prioritizes VR features for safety training, providing a basis for optimizing VR training design (Tusher et al. 2024; Radhakrishnan et al. 2021). This contributes offers a theoretical model for effective VR training designer developers.

Methodological Contributions: This study uses a mixed-methods approach, incorporating observations, semi-structured interviews, and quantitative data from AHP to provide a comprehensive understanding of VR safety training.

- **Mixed methods approach:** The study combines qualitative data from observations and empathy mapping with quantitative data from AHP to robustly analyze VR's impact on safety training, strengthening the validity of the findings (Toyoda et al. 2022; Strojny and Dużmańska-Misiarczyk 2023; Bedenlier et al. 2020). This methodological stringency contributes by demonstrating a comprehensive approach to utilizing VR for safety training.

Practical Contributions: This research offers practical guidance for VR training development and aims to improve real-world safety outcomes.

- **Guidance for VR training development:** The study identifies impactful VR features and training criteria, derived from various research tools, to guide the development of effective programs, developing VR training more practical and targeted (Yoo et al. 2023). This contributes by delivering actionable guidance for VR training design.
- **Improved warehouse safety:** The research demonstrates VR's prospect, as observed through warehouse visits, and reviewing audit techniques to enhance safety training and reduce accidents in warehouses, leading to safety improvements (Hofstra et al. 2018). This contributes by offering an initiative and practical solution to actual safety challenges.
- **Wider VR adoption:** this study encourages its wider adoption in safety training across industries, promoting broader improvements in safety practices (Scorgie et al. 2024; Stefan et al. 2023). This contributes by advocating for the practical application of VR technology for widespread safety enhancement for various similar environments.

Technological Contributions: This study evaluates VR capabilities for safety training and identifies areas for technological improvement based on user feedback through empathy mapping, 9 windows, and critical thinking discussions.

- **Evaluation of VR capabilities for safety training:** The research assesses VR's strengths and limitations in safety training to inform its effective use and maximize its ability (Yoo et al. 2023). This contributes by providing insights into optimizing VR technology for training.
- **Identification of areas for VR technology features focus:** The study prioritized the VR features, based on experts' feedback, that enhance training applications and their benefits. This contributes by guiding future VR technology development for safety training.

6 Research limitations

This study has several limitations that should be acknowledged. The sample size of warehouse visits and VR experts, while providing valuable data, may be limited to: Generalization, The findings of this study may not be fully generalizable to all warehouse environments due to variations in workforce characteristics, safety culture, and technological infrastructure. The focus on specific warehouse types and safety scenarios may also restrict the applicability of the results to other industries or contexts. Additionally, participant bias, where participants may exhibit social desirability bias in their responses, could influence the results.

Furthermore, VR Technology Limitations: The effectiveness of VR training may be limited by factors such as

hardware limitations, software quality, and user experience. This affects the long-term relevance of some findings. Finally, measuring the impact of VR training on safety behavior or accident rates in actual environments.

7 Conclusions

This study has investigated virtual reality's ability to enhance warehouse safety training through a mixed-methods approach, including observations, empathy mapping, the 9-window tool, critical thinking discussions, and the AHP. The findings highlight the diverse hazards present in warehouse environments and the limitations of traditional safety training methods. Our research demonstrates VR utilization to address these limitations by providing immersive and interactive learning experiences. Key VR features, such as simulation realism, immersive interaction, and risk identification, were identified as crucial for effective training. While challenges related to technology and implementation remain, this study offers valuable insights and practical guidance for developing and optimizing VR safety training programs. Ultimately, this research contributes to a safer and more productive work environment by adopting innovative training solutions like VR.

8 Future work

This study lays the foundation for numerous future research opportunities. Further research should explore the knowledge gained and skills learned in VR compared to the traditional methods in real-world warehouse scenarios, focusing on how to enhance the skill transfer and ensure that VR training translates to improved safety practices. Longitudinal studies are needed to assess the long-term impact of VR training on actual safety behavior and accident rates in warehouse environments, providing stronger evidence of VR's effectiveness.

Investigating the capability of advanced VR features, such as motion tracking and AI-driven scenarios, could further enhance safety training outcomes. In addition to that, the role of multisensory integration in VR safety training should be explored further, examining how audio, haptic, and other sensory stimuli can enhance learning and retention.

Developing methods for customizing and personalizing VR training content to address specific individual and workplace needs, using adaptive learning techniques, is another important area. A comprehensive cost-benefit analysis of VR safety training implementation would help organizations make informed decisions about adopting this technology. Exploring how VR training can be seamlessly integrated with existing warehouse management systems and safety

standards to create a holistic safety management approach is also crucial. Further research is needed to address simulator sickness and other adverse effects associated with VR use to improve user comfort and training effectiveness. Finally, investigating the applicability and effectiveness of VR safety training in other high-risk industries beyond warehousing, such as construction, manufacturing, and transportation, would be valuable.

9 Appendixes supporting information

Supplementary data associated with this article can be found in the appendixes.

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Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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