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Enhancing warehouse safety and resilience through virtual reality: A user-centered design approach to training feasibility

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ABSTRACT

Safety training is essential for saving lives and resources, especially in high-risk environments like warehouses. This study investigates virtual reality (VR) as a tool for safety training and utilizes design thinking (DT) processes that apply a user-centered design approach to enhance user experience. A mixed-method design evaluated usability, presence, cognitive load, and simulator sickness with 52 trainees and 12 experts using validated instruments and 5 Whys interviews. Results show high usability, high presence levels, moderate cognitive load, and low simulator sickness, demonstrating VR's feasibility for safety training. Qualitative insights highlight VR's role in improving hazard recognition and compliance. This study offers practical insights into VR's benefits and challenges for safety trainers and facility managers, integrating facility management principles to enhance risk management and training feasibility. This research enables VR technology utilization for effective training experiences, which leads to implementing safety procedures and observing risks in the actual workplace environment.

1. Introduction

Safety is a fundamental concept in supply chain management and logistics, especially in high-risk environments like warehouses where materials are stored and handled [1]. According to [2], industry safety reports, there were over 2.5 million nonfatal injury and illness cases and 851 fatal cases in 2023, with warehouse-related roles, such as laborers and material movers, accounting for more than 77 thousand cases, over a third of which affected workers in their first year [3]. These statistics underscore the severity of warehouse safety issues, including slips, falls, equipment accidents, and ergonomic injuries, which often stem from inadequate hazard recognition and procedural adherence [4–6]. As a result, this study focuses on the implementation of the safety standards and procedures developed, especially for warehouse operations [7] to mitigate the root cause of the accident and enhance hazard recognition and safety compliance [8].

Furthermore, keeping the warehouse environment safe and productive is essential to effective facility management (FM) [4]. A safer workplace is immediately impacted by the organization and waste reduction framework, which provides an organized, cleaned, and standardized work environment and enhances visual management in a manufacturing environment [9], according to lean principles [10]. Traditional training techniques, such as classroom lectures and on-site demonstrations, fail to simulate a complex and dynamic environment

like a warehouse, making safety procedures hard to practice [11]. These limitations underscore the need for innovative training solutions like virtual reality (VR), which can address the shortcomings of traditional methods by providing immersive, interactive simulations of warehouse hazards [12,13]. VR presents a distinctive opportunity to overcome these constraints because of its immersive and interactive features [14], and it can simulate the warehouse workplace environment despite its complexity [15]. VR technology overcomes these shortcomings by providing immersive, interactive simulations of warehouse hazards without real-world risks [12,13]. VR enables trainees to experience realistic scenarios, improving hazard recognition, learning retention, and risk management in a controlled setting [16].

Integrating FM principles such as organized layouts, waste reduction, and standardized workflows [9,10,17] with VR enhances its effectiveness for safety training. When combined with a user-centered design (UCD) approach [18], including design thinking processes [19], VR applications can be tailored to meet the specific needs of warehouse workers, facility managers, and safety experts, ensuring better usability and practical relevance [13]. This research presents an innovative approach using a VR application specifically designed for safety training in warehouses. Through VR integration, standardized warehouse safety training is provided; therefore, all staff members, facility managers, and safety experts receive the same safety guidance and practice. As

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a consequence, trainees can experience and increase their awareness level of safety procedures and hazard identification in a controlled environment by navigating warehouse simulations through VR.

This research investigates the application's needs and compliance with safety trainers' and experts' demands to explore the cause-and-effect correlations through 5 Whys (5W) interviews. The '5W' technique originates from the Toyota Production System (TPS) [20] by delivering a thorough examination of the underlying causes [21]. The 5W is utilized to identify the root causes of an issue by asking 'Why?' until the root causes are found. This research explores safety causes and their effect relationships and tries to better understand the problems faced by safety trainers and experts, ultimately improving the design and compliance of the VR safety training application [22]. Additionally, this study includes further evaluations of the user experience of VR training in warehouse safety to ensure the practicality of the training application for actual use. Experiential learning, a core form of learning-by-doing that allows trainees to conduct VR safety training and physically perform tasks in a simulated environment [23,24], is incorporated into this research [25]. Trainees can practice their technical skills in VR in an appropriate environment, stimulating secure work procedures. This research examines the VR capabilities for safety training in warehouses while considering these factors. This research examines the VR capabilities for safety training in warehouses while considering these factors.

This study aims to enhance warehouse safety training through a user-centered VR application, with three primary goals:

1. Integrating methodologies and design with practical implementation: To enhance VR safety training in warehouses using UCD and learning-by-doing methodologies. Also, to identify the practical benefits and challenges of implementing VR for safety training in warehouses. And finally, to integrate FM procedures with VR features to improve risk management and hazard identification in warehouses.
2. Understanding user requirements for the training: To understand the VR safety training needs in warehouses through qualitative evaluations from safety trainers and experts.
3. User experience assessment: To evaluate the impacts of VR on user experience in warehouse safety training, covering positive outcomes (usability and sense of presence) as well as adverse effects including cognitive load and motion sickness.

The contribution of this work lies in developing a standardized, immersive VR training solution that improves hazard recognition and safety compliance in warehouses, supported by empirical evaluations and a novel integration of facility management principles with VR technology, offering actionable insights for future safety training programs.

2. Literature review

This literature review explores the role of VR technology in revolutionizing safety training in warehouses within facility management practices.

2.1. Traditional training methods (strengths/weaknesses)

Warehouse safety training is initially provided to identify and mitigate the common risks in a warehouse environment and to reduce the accident and incident rates that eventually save human lives. This includes risk management, safety procedures, and hazard identification [7,12]. One of the most effective safety training approaches is implementing FM in the workplace [4,17]. Still, to do that traditionally, the training must be done in the physical workplace and simulate the risks and hazards, which requires resources and affects productivity. This led to significant challenges in enforcing preventative safety measures in real warehouse contexts [26]. Traditional methods,

including classroom lectures, on-site demonstrations, and video-based instruction, offer several strengths, such as being cost-effective, scalable for large groups, and effective for conveying foundational theoretical knowledge [13]. However, they have notable weaknesses, where they lack interactivity and immersion, leading to lower knowledge retention and skill transfer to real-world scenarios [16]. Moreover, simulating hazardous situations in physical environments can be resource-intensive, disrupt operations, and pose actual safety risks, limiting their practicality in dynamic warehouse settings [12]. These shortcomings highlight the need for more advanced training solutions.

2.2. VR safety training methods

VR safety training methods leverage immersive simulations to replicate hazardous scenarios, allowing trainees to practice without real-world risks. VR safety training in warehouses supports visualization, testing, and employee training to enhance occupational and functional safety, as demonstrated in research on VR applications for intralogistics systems [27]. According to Lovreglio et al., VR enables realistic and engaging simulations of hazardous scenarios without exposing trainees to actual risks [28]. Nykänen discusses VR features that enhance employees' hazard awareness abilities by helping them acquire knowledge from hazardous situations in a controlled environment [29]. The ability of VR to improve the way people acquire knowledge is an additional benefit of safety training in warehouses. VR provides an immersive and interactive learning environment by simulating construction workplaces and activities, which improves the recall of safety procedures [30]. Furthermore, according to Getuli et al., VR technologies facilitate the transfer of information among stakeholders, increasing collaborative efforts and enhancing the results of safety training [31]. In many types of industries, supply chains and warehouses play a crucial role in storing a wide range of items for short or long terms, from spare parts, machines, tools, and equipment to final products. VR has been demonstrated to be an efficient tool for safety training in different types of domains [13]. One vital characteristic of VR is its ability to enhance the training experience through an active learning style. An immersive training environment enables a deeper understanding and improved recall of safety concepts. This active engagement assists the trainees in better understanding safety and improves their ability to identify and mitigate risks. For instance, Harris et al. indicates that VR's immersive and interactive characteristics greatly increase trainee engagement when combined with gamification elements, which enhance motivation during safety training sessions [32]. VR provides a solution for safety training in warehouses by providing realistic simulations where the trainee can improve hazard recognition skills, enhance safety knowledge, facilitate information sharing, and enable effective performance assessment. These benefits demonstrate the value of integrating VR into safety training programs to ensure a safe work environment. Critically, while VR methods show superior retention and engagement compared to traditional approaches [13,16], they are not without limitations, including high initial costs, potential for simulator sickness, and the need for technical infrastructure [29]. Warehouse-specific applications, such as forklift simulators, have delivered improved safety and operational performance [33,34]. However, many relevant studies are based on construction or general industry contexts, which limits their direct applicability to warehouse operations [30]. For example, many companies have utilized VR training that leads to safer and more efficient operations [35].

In summary, VR technology presents a feasible method of getting around the limitations of conventional training techniques. VR replicates the intricacies of a real warehouse by creating an immersive and interactive environment in which learners can actively participate in simulated activities [13,16].

2.3. Integration of facility management principles

To understand why and how we use the VR application to implement the facility planning methods [36], starting with the concept, is an integral part of workplace management. This is especially true in warehouses where the likelihood of hazards is high. Facility management significantly reduces safety hazards in warehouses by facilitating an organized and clean workspace [17], along with designing a safe warehouse according to FM principles [37]. Enhancing safety training in VR involves leveraging both facility management and planning. In facility planning, VR can be used to visualize and test various layouts and workflows for warehouses, ensuring that the design minimizes risks and enhances safety. This proactive approach allows us to identify and mitigate hazards before their occurrence [36]. In facility management, VR training simulates an actual warehouse environment, allowing trainees to practice safety procedures and emergency responses [17,37]. This experience provides employees with outstanding safety standards. By integrating principles of facility planning and facility management into warehouse VR safety training, safety standards can be elevated, and workplace management and organisation allows us to be strengthened throughout both warehouse design and daily operations to create a safer working environment. The current study integrates the facility management concept into VR safety training. VR provides trainees with hands-on experience implementing safety guidelines in a simulated warehouse, which allows them to comprehend their responsibility for maintaining a productive and safe work environment with high standards. Consequently, integrating FM with VR allows for proactive risk mitigation, but empirical evidence in warehouses is limited, often extrapolated from manufacturing contexts, and may overlook implementation challenges [38,39].

2.4. Experiential learning (“learning by doing”)

Learning-by-doing is an experiential learning approach that emphasizes hands-on, active learning experiences [23,40], especially in VR applications [25]. This method focuses on the principle that trainees can apply their knowledge and skills in a practical context; they retain them more successfully [24]. VR training is especially well-suited to the learning-by-doing methodology because of its immersive and interactive features, which let users participate in realistic simulations of typical safety tasks. In this study, learning through practice has been applied in a variety of ways to VR safety training in warehouses, including: First, design training that simulates actual safety situations. When trainees complete tasks within a simulated warehouse, they interact with the virtual environment and practise safety procedures without exposure to physical hazards. Later, by enhancing critical thinking and problem-solving skills, trainees identify areas where their safety knowledge requires improvement by illustrating their experiences in VR exercises. Ultimately, they can practice addressing any safety issues that they may encounter in the real world. While this approach enhances retention and skills, it requires careful design to avoid overwhelming users [18], and its feasibility in warehouses needs more targeted studies beyond general applications [25].

2.5. Research gaps in warehouse-specific VR training research

Despite these promising benefits, significant gaps remain in warehouse-specific VR training research. Most studies focus on construction [12, 30] or general VR applications [13,41], with limited empirical data on warehouses, where unique challenges like high-volume material handling and intralogistics prevail [27]. Key gaps include feasibility evaluations, training benefit analyses in warehouse contexts, scalability for diverse workforce demographics, and integration with existing FM systems. Furthermore, there is a notable lack of research into customized and UCD frameworks that allow VR environments to be tailored to specific user profiles and unique organizational workflows, which is essential for maximizing user acceptance and training relevance. Addressing these could enhance VR’s practical adoption in warehouses, which enhances safety training practicality.

3. Methodology

This study employs a mixed-method quasi-experimental design to investigate VR safety training for warehouses. Through developing and evaluating an immersive application designed particularly to fulfill the safety procedures through the facility management for warehouse staff and safety auditors, this methodology takes into account the UCD method. This entails that the application has been developed with the particular needs and requirements of safety experts and trainees in mind. VR integrated a learning-by-doing approach into its application, enabling trainees to engage in practical simulations of warehouse safety activities and learn about safety standards. A pilot study with 10 participants from one safety center was conducted to evaluate initial adaptability and refine our methodologies. In the main study, 52 participants were included as trainees from safety centers randomly, aged 23–42 years. The research was conducted during the first and second semesters of 2023–2024.

The quasi-experimental design lacked a control group due to resource constraints but included post-training assessments to measure changes in user experience. While direct comparisons were not feasible, indirect validation of VR’s relative advantages is supported by existing literature, where VR shows superior knowledge retention and engagement compared to traditional methods [13,26]. This strengthens the study’s feasibility evidence, though future controlled studies are recommended. The VR application was developed using Unity and Oculus Quest 2 and 3, integrating a learning-by-doing approach to simulate realistic warehouse safety tasks. The methodology followed a structured process, detailed in the research procedures sub-section, to ensure user familiarity and effective training outcomes.

3.1. Participants

The main study included 52 trainees, selected using simple random sampling from a pool of eligible trainees across three safety centers. Eligible trainees were identified based on their enrollment in safety programs. To improve representativeness, the selected centers cover a range of industries and corresponding warehouse operations, reflecting diverse operational contexts involving different storage and scaling processes. Specifically, the centers represented a combination of automated and manual warehouses, though all were located in Jordan, potentially limiting geographical diversity. No pre-assessments were collected, as the study focused on feasibility via post-training user experience rather than comparative effectiveness. Demographic data as shown in Table 1 were analyzed to confirm variability in age, where 17.3% aged 18–24, 65.4% aged 25–34, 17.3% aged 35–42, gender was 65.4% male and 34.6% female. Regarding educational attainment, the majority of the participant cohort (86.5%) held a bachelor’s degree. This distribution is representative of the professional sector, as a bachelor’s degree is the mandatory minimum educational prerequisite for obtaining a safety supervisor license. No pre-assessments were collected, as the study focused on feasibility via post-training user experience rather than comparative effectiveness. Demographic data as shown in Table 1 were analyzed to confirm variability in age, where 17.3% aged 18–24, 65.4% aged 25–34, 17.3% aged 35–42, gender was 65.4% male and 34.6% female. Regarding educational attainment, the majority of the participant cohort (86.5%) held a bachelor’s degree. This distribution is representative of the professional sector, as a bachelor’s degree is the mandatory minimum educational prerequisite for obtaining a safety supervisor license.

Table 1 presents breakdowns by safety experience: 88.5

The pilot study involved 10 participants. While the main study’s sample size was determined based on a power analysis targeting a moderate effect size for quantitative measures such as usability and presence. For the qualitative component, 12 safety trainers and experts were interviewed using the 5W methodology, sufficient to achieve thematic saturation for identifying user needs and challenges [42]. Of

Table 1
Demographic distribution of 52 participants of the main sample.

Feature	Sub-feature	Number	Percentage
Age group	18–24 years old	9	17.30%
	25–34 years old	34	65.40%
	35–42 years old	9	17.30%
Gender	Male	34	65.40%
	Female	18	34.60%
Educational level	Technical diploma	2	3.80%
	Bachelor's	45	86.50%
	Master's	5	9.60%
Safety experience	Yes	46	88.50%
	No	6	11.50%
VR experience (Prior use)	Yes	14	26.90%
	No	38	73.10%
Gaming experience	Yes	31	59.60%
	No	21	40.40%

the 70 participants who partially participated in the main results, three cases were excluded for detailed analysis due to incomplete data. Additionally, the dropout rate was primarily due to technical difficulties with VR headsets, scheduling conflicts with work commitments at the safety centers, and, in some cases, discomfort from motion sickness. Despite the dropout rate, the participants who completed the study provided sufficient data for robust within-subject comparisons and qualitative insights, as supported by the power analysis and thematic saturation. This limitation is further discussed in the Limitations subsection. The demographic distribution, shown in Table 1, indicates that participants were primarily with prior safety experience with 88.5%, with only 26.9% having VR experience and 59.6% having gaming experience, reflecting varied familiarity with virtual environments.

3.2. Materials and application design

3.2.1. Application design

Utilizing design thinking and UCD, this research focuses on designing the application to align with user needs and preferences [19]. Steps in Fig. 1 provide a detailed visual representation of the design thinking process used to develop the VR application.

In summary, the application, as shown in Fig. 2, for warehouse safety training was designed to meet the specific needs of trainees, trainers, and experts, using the UCD process. This approach ensures warehouse safety requirements are addressed in the VR training environment.

3.2.2. Technical aspects

The technical aspects of the VR application for safety training in warehouses were carried out by integrating the content with the latest design software and game engine, Unity, and utilizing the latest available HMD unit as hardware using Oculus Quest 2 and 3. This integration is shown in Fig. 3.

• Content:

To create content for your VR safety training, this research determined the following:

- Target Audience: The target audience consisted of safety trainers, safety experts, logistics employees, and warehouse employees.
- The training aims to strengthen warehouse safety proficiency, risk management, and the implementation of risk mitigation and hazard elimination procedures. It focuses on tackling underlying root causes to reduce both the likelihood and severity of risks.

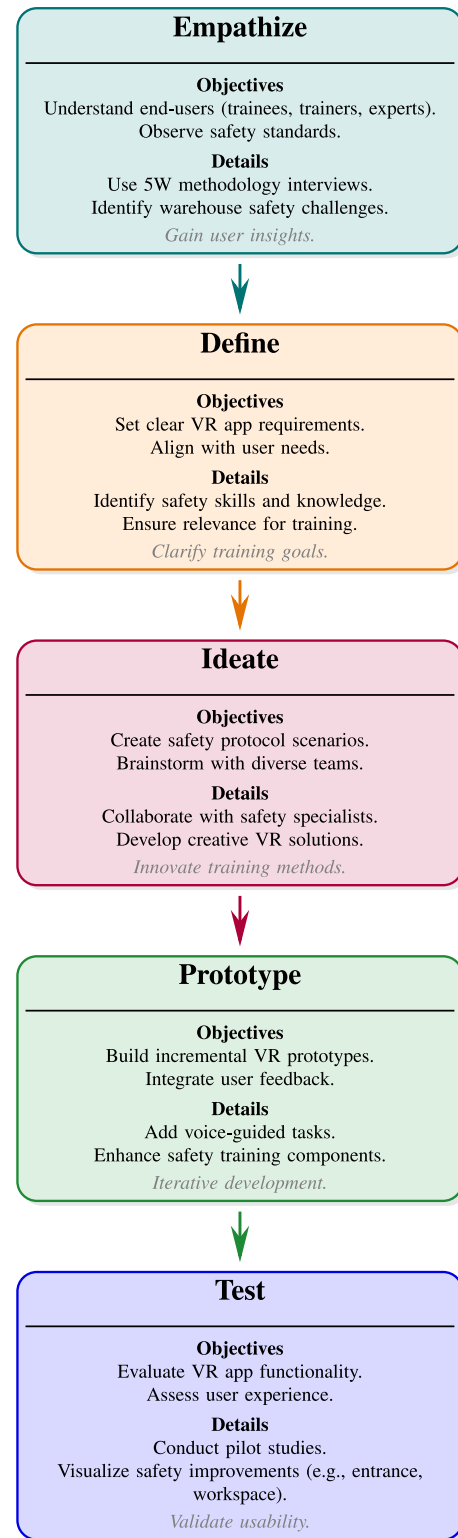


Fig. 1. Design thinking steps for VR warehouse safety.

- Elements of a virtual space environment: creating virtual content that covers various warehouse elements such as storage space, item types, shelves, ladders, doors, ventilation, lighting, windows, forklifts, electrical sources, safety equipment (fire extinguishers), waste management, and more.

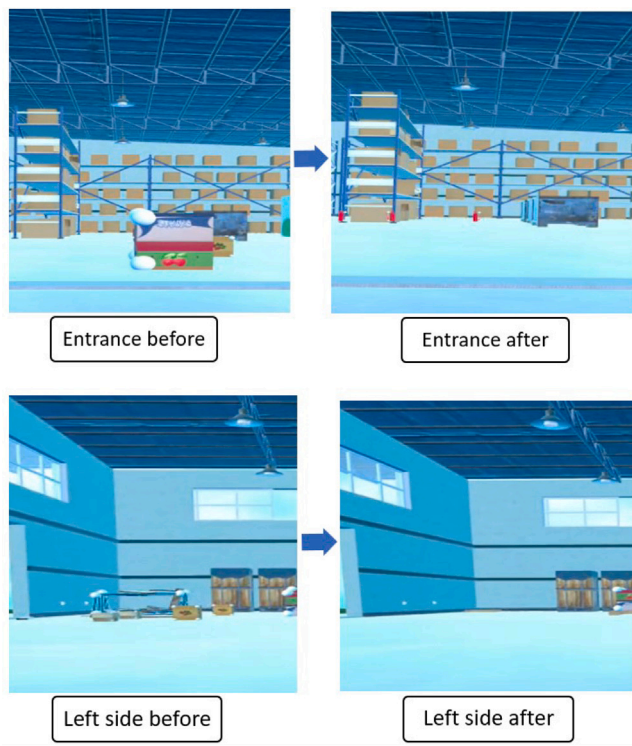


Fig. 2. Warehouse components.

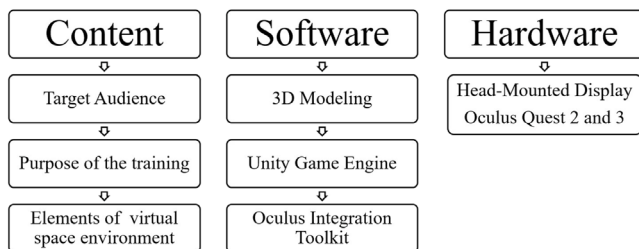


Fig. 3. Content and technical components virtual reality application.

• Software:

- 3D Modeling: Create the virtual environment and safety equipment using Blender as 3D modeling software. This involves designing the warehouse structure and integrating appropriate elements. The 3D modeling process used high-precision, high-poly models for performance; the modeling cycle involved iterative prototyping, starting from low-fidelity wireframes to fully functional models, incorporating user feedback at each stage.
- Unity 3D Game Engine: To create the VR experience, Unity 3D Game Engine (version 2022.3.10f1) has been used. Unity is a platform for developing interactive and immersive simulations. Utilize prefabs from the Unity Asset Stores and other sources to enhance the development. VR interaction logic was implemented using Oculus Integration, with controller operation mapping for grip and trigger actions, like grip to grab objects and trigger to activate tools or confirm tasks; task triggers were based on proximity distances in the virtual environment, for example, handling objects when within 5 centimeters of simulated boxes, and event scripts in C# compatible with Oculus Quest, allowing users to interact with virtual objects to accomplish tasks; movement was

facilitated using the thumbstick on the controller for normal navigation inside the environment.

- Oculus Integration Toolkit: For VR, the Oculus integration toolkit was used. This toolkit ensures that the Unity development environment and the Oculus Quest headset engage easily.

• Hardware:

- HMD: Oculus Quest 3 and 2 were selected as the VR headset. Cost and quality were considered when selecting a headset that will provide an intended VR training experience. The Oculus Quest is a head-mounted display device that provides trainees with an immersive visual experience.
- The VR experience was developed on a laptop with an Intel Core i7-11700H CPU, 16 GB RAM, and an NVIDIA GeForce RTX 3050 Ti graphics card with 4 GB of memory.

The VR application featured specific safety scenarios to simulate realistic warehouse tasks, including sorting items to maintain an organized workspace, identifying hazards like misplaced items, electrical risks, and practicing emergency procedures like fire extinguisher use, as shown in Fig. 2. User interactions were facilitated through Oculus Quest 2/3 controllers for navigation and object manipulation, with voice-guided instructions providing step-by-step task guidance to enhance engagement. Hardware requirements included an Oculus Quest 2 or 3. These specifications ensure replicability, allowing researchers to recreate the VR environment for similar safety training studies.

To accommodate users with varying digital literacy and physical abilities, the VR design incorporated user-friendly features informed by the UCD process and findings from special cases as detailed in the Result and Discussion. For low digital literacy, simplified interfaces with intuitive menus and an onboarding tutorial were included to guide novices through VR navigation and controller use. For physical accessibility, the application supported both seated and standing positions, with Oculus Quest 3's pass-through mode enabling users to see the real world to reduce disorientation, particularly for those with balance issues. These adjustments supported inclusivity, making the VR training accessible to trainees with diverse technical and physical capabilities and thereby increasing its practical value for warehouse safety training.

The technical aspects involve creating tailored content for the target audience, utilizing powerful software tools Unity and 3D modeling software, and selecting appropriate hardware, Oculus Quest, to deliver an effective and engaging VR safety training experience in warehouses.

3.3. Procedure

Fig. 4 provides a structured flowchart of the research methodology, illustrating the phases of design, data collection, and analysis.

The pilot study involved 10 participants from one safety center to assess initial feasibility and refine the VR application and methodology, consistent with typical sample sizes for VR feasibility studies [43].

Stepping into VR safety training, the training session involves a multi-step process to ensure user familiarity and comfort with the equipment. The VR safety training process conducted as part of the main study (Fig. 4) followed a multi-step procedure to ensure user familiarity and comfort with the equipment. Each training session lasted approximately 60–90 min, with two sessions conducted per safety center, totaling six sessions across three centers during the first and second semesters of 2023–2024. These sessions followed a structured four-step process:

- First, instructions and equipment setup: the trainee received detailed instructions on how to wear and use the VR headset, including the head-mounted display (HMD) and its controllers. This has taken place in a vast room setting for proper usage.

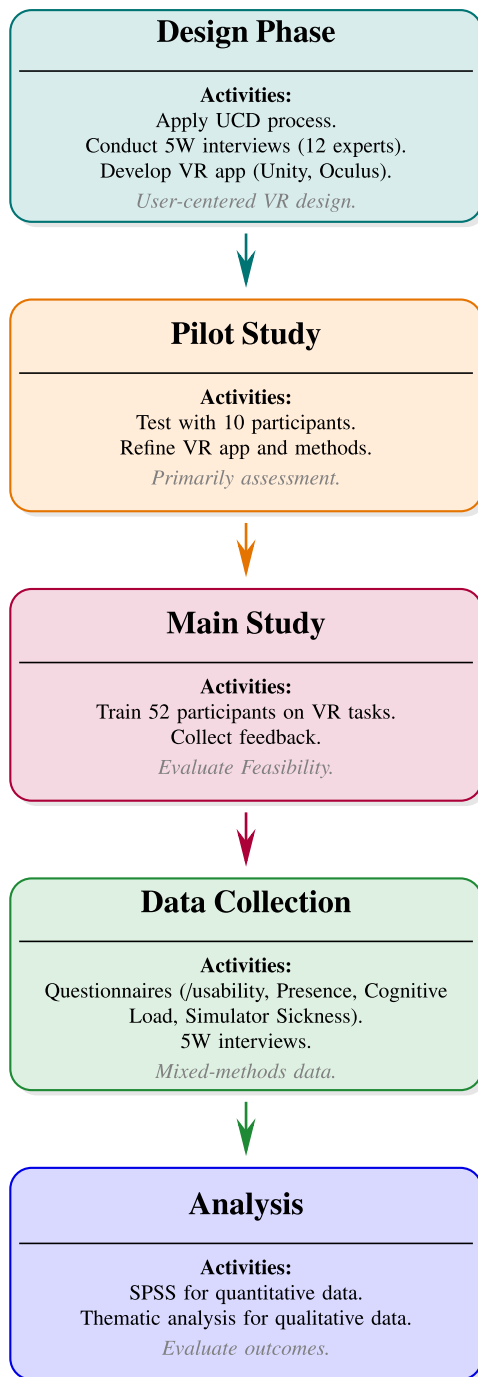


Fig. 4. Mixed-methods research framework.

- Second, familiarize the trainee with the VR environment preview by utilizing a live stream displayed on a 2D screen using a phone or laptop, so the trainee can see the 3D environment of the VR experience, giving users a brief overview of what to expect within the virtual space.
- Third, VR Training Initiation, where the actual VR training session began once trainees were settled in and prepared.
- Fourth, in interactive training, trainees actively participated in the VR training, putting their knowledge of the FM into practice by completing several tasks within the virtual warehouse environment. At this stage, users were able to walk through the VR environment and hear prerecorded instructions on how

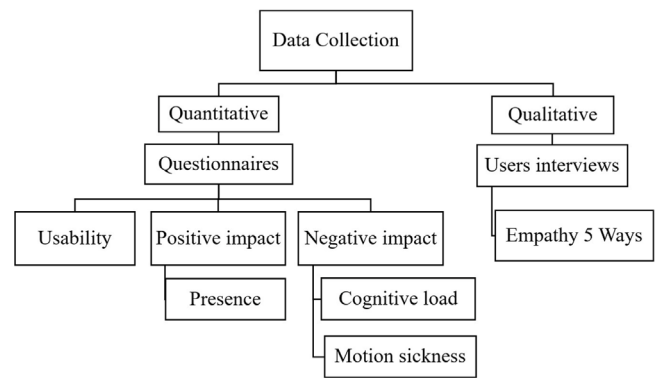


Fig. 5. Data collection process.

to organize a workplace using FM and safety procedures. The instructions involved structured tasks to be implemented. This involves sorting all items in the warehouse and removing any unnecessary ones to keep the warehouse organized. Subsequently, items should be arranged within designated storage areas to ensure easy access and accessibility. Maintaining a clean and hazard-free environment.

Only post-assessments were employed because the study's aim was to evaluate VR's feasibility in terms of usability, presence, cognitive load, and sickness after the exposure session, aligning with exploratory designs for novel applications [44]. According to Sudiarno's review, 33% of the studies are based on a single experimental group [41], and Stefan finds that 38.97% are based on direct evaluation [13]. Pre-assessments were deemed unnecessary for this feasibility focus, though future effectiveness studies could incorporate them.

To understand user needs, interviews with 12 safety trainers and experts were conducted using online meeting tools or in-person meetings, based on participant availability, as described in the Participants subsection. Post-training assessments, lasting 20–30 min, were administered using Google Forms and paper-based questionnaires to evaluate usability, presence, cognitive load, and simulator sickness, as detailed in the Data Collection and Analysis subsection. No pre-training assessments were conducted, as the study's exploratory design focused on assessing the feasibility and user experience of integrating novel VR technology into warehouse safety training, consistent with resource constraints and the novelty of VR in this context [43]. This approach aligned with the UCD process, prioritizing immediate user feedback to evaluate technology adoption. The pilot study provided preliminary insights into feasibility, reducing the need for baseline assessments, while validated instruments and qualitative interviews ensured robust evaluation of VR integration.

3.4. Data collection and analysis

This study uses both quantitative and qualitative techniques for data collection and analysis through questionnaires and interviews, as shown in Fig. 5. To understand the current state of VR technology deployed for warehouse safety training, this study begins with a descriptive analysis. Furthermore, the study includes exploratory components as it determines the advantages and disadvantages in detail regarding employing VR training task environments.

3.4.1. Qualitative evaluation

The 5 Whys method was chosen over other qualitative tools, such as open-ended interviews or focus groups, because it offers a structured, iterative approach specifically designed for root cause analysis, which is particularly effective in safety and operational contexts like warehouses, where identifying underlying issues can directly enhance

Table 2
5W interview criteria.

Criteria	Description
When	Empathize Stage
Purpose	Understanding safety trainers needs for warehouse safety.
Focus	User problems and expectations. User-centered design.
Methodology	This tool gather detailed information to understand user needs.
Participants	Trainers and safety experts.
Outcomes	Understanding user-requirements for VR training.

training design and compliance [20,21]. Unlike broader exploratory methods, 5 Whys ensures depth by systematically drilling down to fundamental causes, making it more efficient for our feasibility-focused study. To follow the interpretivist research philosophy [45] for VR warehouse safety training, qualitative research has been conducted. This approach enables a deep understanding of trainers’ perspectives. Interviews with 12 safety trainers and experts were conducted using the 5W methodology [20–22], with open-ended questions about their key points and importance as shown in Table 2. To find patterns and themes in VR warehouse safety training according to FM and the VR safety training challenges, thematic analysis has been applied to observational data and interview transcripts.

Several initial investigations and interviews have been conducted using the 5W technique to emphasize the need to understand the root causes [21,46] behind the demands of warehouse staff and safety auditors for VR safety training incorporating the FM.

3.4.2. Quantitative evaluation

The quantitative research results provide a comprehensive examination of how VR impacts various aspects of the user experience through descriptive analysis, including positive and negative factors. The descriptive aspects involve the investigation of novel concepts and ideas to determine the advantages and difficulties of utilizing VR in warehouse safety training.

Usability. System Usability Scale (SUS), a commonly used instrument to measure technology usability, is applied to the evaluation of warehouse safety training in VR [47]. This research slightly modified the questionnaire for VR applications in safety training. Every item is rated using a five-point Likert scale, with 1 representing ‘strongly disagree’ and 5 representing ‘strongly agree’.

Presence. Presence, which can be described as the feeling of being physically present in the virtual environment, holds immense significance in the field of VR safety training research. Presence plays an important role in enhancing the effectiveness of VR training and influencing trainee engagement. Researchers use a presence questionnaire (PQ) to measure trainees’ presence levels effectively [48,49].

PQ is essential for new VR applications, especially in safety training. They provide a standardized measure, enabling researchers to compare findings across different studies and training programs. Also, it takes into account the factors that influence immersive experiences. These factors can guide the design, development, and evaluation of VR safety training programs, thereby enhancing safety practices in actual work, reducing workplace accidents and incidents, and saving human lives and resources.

Cognitive load. Cognitive load measurement is essential in VR safety training for enhancing learning quality [50,51]. While VR technology provides immersive experiences that have transformed safety training, effective training requires the management of cognitive load factors, both the mental load and mental effort required to process and comprehend VR environment content.

Trainers can prevent exhaustion by adjusting the activity level, assistance, or types of features by measuring the cognitive load, which assists in identifying possible overload situations. The appropriate level of challenge keeps trainees interested, while cognitive load also affects motivation and engagement.

Simulator sickness. The Simulator Sickness Questionnaire (SSQ) is used in this research to evaluate the VR application environment and identify trainees who are subjected to VR. The objective is to understand how VR causes motion sickness. Participants reported only the symptoms they experienced; this ensures a comfortable method of providing VR safety training, which eventually creates an efficient and effective training environment. The SSQ [52] offers a quantitative assessment of the intensity of symptoms that affected the training. The SSQ is considered a tool used to measure the level of discomfort trainees experience due to locomotion and interaction in a VR environment.

3.4.3. Data analysis

The VR safety training experience was analyzed using SPSS software for testing the quantitative data. The analysis focused on user experience, identifying both positive and negative impacts. Positive aspects included usability and presence level, while negative ones included cognitive load and motion sickness. Thematic analysis was used to identify recurring themes and patterns in the interview data for the qualitative data. Eventually, this study determined the feasibility of delivering a new method with VR training experiences to trainees. The research gathered a holistic understanding of the training needs and user reactions to the VR safety training program through the integration of data from questionnaires and 5W interviews. The research contributes to an intense understanding of the benefits and challenges of VR safety training, providing comprehensive details for decision-makers, safety instructors, researchers, and investors to start transforming their training and utilizing the latest technologies.

4. Result and discussion

This section presents the findings from a study that defined the training needs and evaluated the user experience of VR technology for safety training in warehouses. The study analyses both qualitative and quantitative data to provide comprehensive information regarding training and user reactions.

4.1. Qualitative analysis

This research employs the 5W technique to identify the root causes and align VR training with actual needs for VR safety training in warehouses, incorporating FM [20–22]. It provided an immersive and realistic environment for trainees to practice safety procedures, enhancing their skills. The application addressed challenges in adapting to new technology, resistance from workers, and a lack of experience with immersive technology. By integrating these elements, VR created a comprehensive training solution suited to warehouse safety requirements, ultimately enhancing productivity, reducing costs, and ensuring compliance. Qualitative results, summarized in Table 3, highlight key points such as the importance of training in warehouse safety, FM, VR application benefits, and challenges.

First, the importance of training in warehouses lies in preventing accidents and injuries, enhancing productivity, and reducing costs related to lost time and unsafe conditions. Also, continuous training ensures compliance and provides employees with an understanding of the importance of safety.

Second, the importance of FM for warehouse safety comes to ensure a safe working environment, preventing hazards and resource loss, while promoting organized and secure workspaces. Also enhances risk mitigation, improves efficiency, and empowers employees for safety decisions.

Third, the importance of a VR application for safety training in warehouses came when it provided an immersive and realistic environment for safety training, enabled trainees to practice safety procedures, received customized training, and enhanced their safety skills. It creates an enjoyable and effective learning experience, improving information retention and skill acquisition through interactive methods.

Table 3

Summary of key points and percentages of qualitative result from 12 safety trainers and experts.

No.	Key points	Percentage
1	Importance of Training in Warehouse Safety	
	High accidents, injuries, reduced productivity	100%
	High time and costs	75%
	High Unsafe acts, conditions	83.33%
	Mitigate risks, safety skills	66.66%
	Continuous training, compliance	58.33%
2	Importance of Facility Management for Warehouse Safety	
	Enhance safety operation environments	83.33%
	Prevent hazards, resource loss	66.66%
	Secure, organized work environments	66.66%
	Reduce risk identification, mitigation	75%
	Improve efficiency, effectiveness	66.66%
	Empower employees, safety decisions	66.66%
3	Virtual Reality Application for Safety Training in Warehouse	
	Immersive, realistic environment	100%
	Practice safety procedures	50%
	Safe, enjoyable learning environment	83.33%
	Effective training	83.33%
	Interactive learning, retention	75%
	Gamification, skill retention	75%
4	VR Safety Training Challenges	
	Adapting to technology	75%
	Additional training for VR systems	75%
	Resistance from older workers	75%
	Lack of immersive tech experience	50%
	Time, resources for training	41.66%
	organizational support	50%
	Integrating VR into training programs, lack user experience evaluation	58.33%

Lastly, VR safety training challenges cover difficulties in adapting to new technology, additional training required for VR systems, resistance from older workers, lack of workers experience with immersive tech, limited exposure to new tech, traditional methods, time and resource constraints, lack of organizational support, integrating VR with training programs and customized training, and lack of user experience evaluation and feedback.

By understanding the safety training design needs through the pre-design interview, the VR application has been developed to address them directly. This included focusing on safety practices and procedures, including the FM procedure, mitigating VR challenges, and utilizing VR capabilities to enhance learning and retention. This user-centered approach provided a strong foundation for the design and prototyping phases of the VR application development process and provided the correct map for the VR developers.

4.2. Quantitative analysis through questionnaires

In this section, we present a detailed quantitative analysis of the data collected through questionnaires. The main objective is to evaluate the user experience of the VR safety training application. We examine the correlation in the demographic distribution of the participants to provide a relation for the subsequent analyses. Following this, the SUS, presence, cognitive load, and motion sickness were tested. These analyses offer a comprehensive understanding of the user experience and the impact of the VR application on trainees' reactions to new technology.

The breakdown of participant demographics and backgrounds provides a foundation for understanding the findings of the VR safety training experience. By analyzing the data in conjunction with the user experience analysis, this approach gained valuable insight into the value of VR training for this specific population. A Spearman

Table 4

System usability scale result.

	Question	Mean	SD	Note
1	I think that I would like to use this VR safety training frequently.	4.6154	0.69038	
2	I found the VR safety training unnecessarily complex.	1.5385	0.64051	Negative
3	The VR safety training needed the support of a technical person to be able to use this system.	1.5577	0.75182	Negative
4	I think that I would like to be able to use this VR safety training frequently.	4.3269	0.73354	
5	I found the various functions in this VR safety training were well integrated.	4.3269	0.75980	
6	I think there was too much inconsistency in this VR safety training.	1.6923	0.82933	Negative
7	I can imagine that most people would learn to use this VR safety training very quickly.	4.3462	0.96781	
8	I found the VR safety training very cumbersome to use.	1.4808	0.61006	Negative
9	I felt very confident using the VR safety training.	4.3269	0.73354	
10	I needed to learn a lot of things before I could get going with this VR safety training.	1.8269	0.83363	Negative

correlation analysis was conducted to find the relationships between demographic variables and trainee experiences. The analysis revealed a moderate correlation (coefficient = 0.307) between gender and gaming experience. This explains why men tend to have more gaming experience than women. Also, there was no correlation (coefficient = 0.077) between gender and VR experience, while both genders have similar levels of familiarity with VR technology.

4.2.1. Usability

The SUS questionnaire result as shown in Table 4 and Fig. 6 has high internal consistency, with a Cronbach's alpha of 0.806. The VR safety training application demonstrates high usability, as indicated by the interpretation of the SUS score as shown in Table 4. This score indicates a positive user experience and indicates that the application is easy to navigate and interact with for warehouse safety training purposes. The Box-plot in Fig. 6 shows a high median usability score, indicating excellent ease of use, with a narrow interquartile range reflecting consistent user experiences. Few outliers suggest robust usability across participants, supporting the feasibility of VR for effective warehouse safety training.

The SUS mean score is derived through several calculations, from a Likert scale (1–5) to a final score between (0–100). There is also a percentile ranking provided by the SUS score. According to Sauro [53], a score of 68 or higher indicates above-average user satisfaction, while a score lower than 68 specifies below-average. The VR application in this study received a usability score of 87.69, which is considered higher than the average of other systems [47,54].

As a result, the VR safety training application for warehouse has positive aspects, as most trainees agree to use VR safety training more frequently and they find its functions to be well-integrated. They were at ease utilizing the application as well. Positive aspects are indicated by low scores on reverse-scored questions, where trainees typically disagree with the system's complexity or inconsistency and do not require a lot of training. The VR safety training application has high usability, as evidenced by its overall high SUS score. On the other hand, the standard deviation (SD) values indicate response variability with consistency in the participants' feedback.

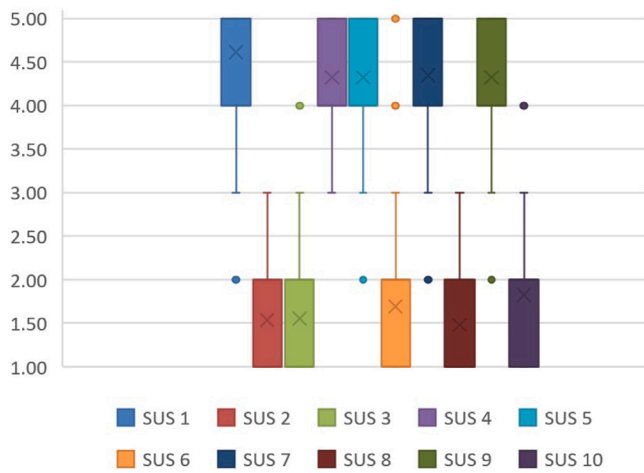


Fig. 6. Box plot of System Usability Scale (SUS) scores for the VR safety training application. SUS 1 to 10 represents the question number.

Table 5

Sub-scales of the presence questionnaire results.

Presence Sub-scales	Items	Means	SD
Factor 1: Involvement	12	5.8093	0.61133
Factor 2: Sensory Fidelity	6	5.8462	0.81238
Factor 3: Adaptation/Immersion	8	5.7548	0.70231
Factor 4: Interface Quality	3	5.5962	0.92257

4.2.2. Positive impact; presence

The PQ result demonstrated high internal consistency, with a high-reliability Cronbach's alpha of 0.941. Table 5 and Fig. 7 demonstrate a high sense of presence, where all sub-scales on the PQ had mean scores greater than 5, where the minimum is 1 and a maximum is 7. The higher the mean scores, the better the perceived sense of presence in the VR environment. Box plot in Fig. 7 of Presence scores, assessing the sense of immersion in the VR safety training environment. The high median score indicates strong user involvement, with a tight spread suggesting consistent immersion. Minimal outliers highlight the VR application's ability to create a realistic and engaging training experience, enhancing hazard recognition in warehouse settings. This indicates an overall useful experience with a feeling of presence in the VR training environment. This implies that the VR application effectively immersed the users in the simulated warehouse and increased their sense of interaction and navigation with the training content.

All factors were rated positively, as their average scores are above the midpoint of the scale. The first factor was involvement, with a 5.809 mean and 0.611 SD. This score indicates a high sense of engagement and absorption among the trainees in the VR training experience. The main reason was the application's ability to provide trainees with a realistic sense of control, which enabled them to navigate within the virtual warehouse and interact with objects. Furthermore, the trainee is fully engaged in the training scenario, which keeps them interested in learning safety procedures in the warehouse environment. The second factor is sensory fidelity, with a mean of 5.846 and an SD of 0.812. A high rating here indicates that the VR environment provided a realistic sensory experience. VR apps can create a highly immersive experience that fools the brain into feeling like you are present in the virtual world. This is achieved via high-quality graphics, realistic interactions with virtual objects, and immersive navigation in the virtual space, all of which are fundamental aspects. The third factor, adaptation/immersion, with a mean of 5.754 and an SD of 0.702. This score still indicates a positive experience, even though it is lower than the other sub-scales. Trainees adapted well to the VR environment, feeling comfortable and oriented within the virtual space. This comfort

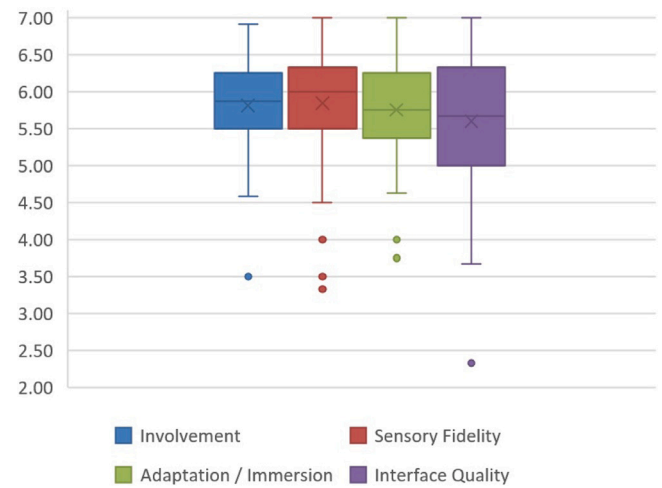


Fig. 7. Box plot of Presence Questionnaire scores, assessing the sense of immersion for 52 trainees.

level allowed them to concentrate on safety training objectives rather than struggling with VR hardware. The SD shows some variability in the participant's experiences. Some trainees have adapted more readily than others; this feedback highlights the improvement in the onboarding process. The fourth factor is interface quality, with a mean of 5.596 and an SD of 0.922. This score is lower than the other, but still within a positive range. It indicates that the VR interface was generally usable, but there is an opportunity for improvement in the interface. The higher SD here indicates a wider range of participant experiences. Some trainees have found the interface easy to use, while others have encountered some difficulties. This emphasizes how essential it is to keep improving the interface in response to user feedback to ensure simple interaction for all trainees. The multivariate tests (Pillai's Trace: 0.090, F: 1.624, Sig.: 0.196; Wilks' Lambda: 0.910, F: 1.624, Sig.: 0.196; Hotelling's Trace: 0.099, F: 1.624, Sig.: 0.196; Roy's Largest Root: 0.099, F: 1.624, Sig.: 0.196) show no significant differences between the four factors; involvement, sensory fidelity, adaptation/immersion, and interface quality as all significance levels are greater than 0.05.

Overall, the PQ results show that trainees' sense of presence was successfully induced by the VR application. The feeling of 'being there' in the virtual warehouse provided the training with more engagement experience.

4.2.3. Negative impact; Cognitive load

The Cognitive Load Questionnaire assesses the perceived cognitive load experienced by learners during a learning activity. It measures two aspects of cognitive load: mental load and mental effort. The mental load is the trainee's requirement to understand the learning material and its perceived difficulty; on the other hand, mental effort occurs when learning activities' overall mental demand as well as the perceived effort necessary for completing their tasks [55]. To assess cognitive load in VR safety training, a dedicated questionnaire was developed based on the theoretical frameworks of [50,51]. This questionnaire comprises eight items on a six-point Likert scale, with five items for mental load and three for mental effort. The questionnaire demonstrates strong consistency with Cronbach's alpha of 0.86 for mental load and 0.85 for mental effort, indicating its reliability in measuring cognitive load.

The results in Table 6, demonstrate that the VR warehouse safety training application has a moderate mental load (mean 1.9880, SD 0.6317) and mental effort (mean 1.6923, SD 0.70122). The application's strengths include its engaging and interactive nature and learning-by-doing activities. However, there are areas for improvement in managing cognitive overload for some individuals by considering

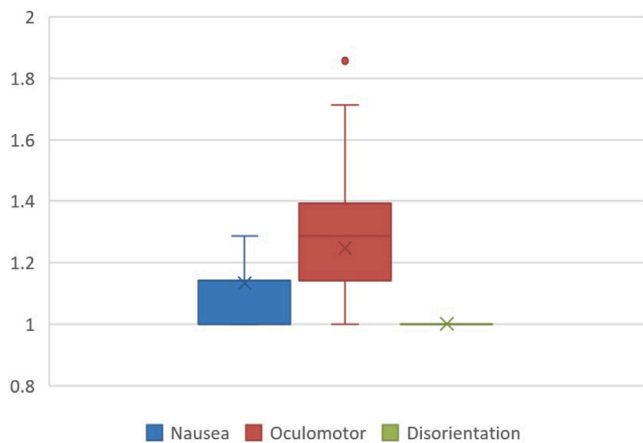


Fig. 8. Box plot of cognitive load scores, measuring mental effort and load for 52 trainees.

Table 6
Cognitive load results.

Cognitive load	Mean	SD
Mental load	1.9880	0.63170
Mental effort	1.6923	0.70122

Table 7
Motion sickness results.

Symptoms	Mean	SD
Nausea	1.1300	0.09700
Oculomotor	1.2473	0.18576
Disorientation	1.0000	0.00000

their differences. The variability in mental load suggests that some trainees received a benefit from monitoring and support during the VR experience to reduce their workload.

Box plot in Fig. 8 shows that the moderate median score reflects manageable cognitive demands, with a moderate interquartile range indicating variability in user experiences. Outliers suggest areas for refining training content to reduce cognitive overload, supporting effective learning in warehouse safety training.

4.2.4. Negative impact; Motion sickness

Table 7 shows the results of the motion sickness symptoms experienced by trainees using a VR application for warehouse safety training. It reports the mean (average) and SD for each symptom. The study found that trainees generally experienced mild nausea on average, with a mean score of 1.13 and an SD of 0.097. Oculomotor problems were similar, with a mean score of 1.2473 and an SD of 0.18576. However, the lower SD indicates lower variability among participants, with some experiencing these issues more intensely. The most remarkable finding was the score of disorientation, indicating that on average, trainees reported no disorientation while using the VR application.

Box plot in Fig. 9 of Simulator Sickness Questionnaire scores, evaluating motion sickness during VR safety training. The low median score indicates minimal oculomotor and nausea symptoms, with no reported disorientation and a narrow spread, confirming user comfort. This supports the VR application's suitability for prolonged training sessions in warehouse safety contexts.

This indicates that all participants reported no encounter of disorientation. Overall, the VR safety training application motion sickness results are well-tolerated, with mild symptoms and no disorientation reported by trainees.

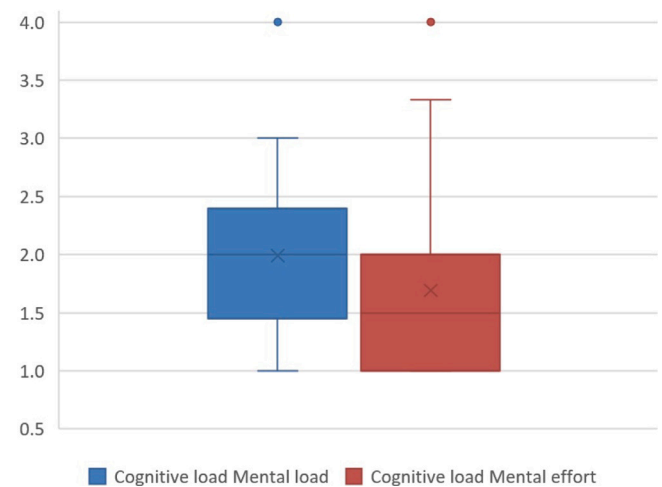


Fig. 9. Box plot of Simulator Sickness Questionnaire scores, evaluating motion sickness for 52 trainees.

4.2.5. Special cases

During the investigation process, three trainees were identified who faced significant challenges using the VR application due to their lack of prior gaming or VR experience and their behavioral reactions. They were excluded, not from the 52 main participants because they were unable to accomplish the task. This highlights the importance of considering user experience for beginners when designing VR training programs.

The first trainee, a 24-year-old female, struggled with balance while standing with the VR HMD. To solve this, her position was adjusted to a sitting position, and secondly, she was provided with an Oculus Quest 3 using pass-through mode. This allowed her to see the real world overlaid with digital content, which improved her comfort level. Additional guidance was provided while she was able to go through the VR menu while viewing the VR experience. The navigation process was conducted using a phone live stream, and she got used to it. The second and third trainees, both male, 45 and 49 years old, had difficulties using the VR controllers even after repeated tries. This is because they lacked an understanding of VR controller functions and interaction procedures. However, they were able to navigate the VR environment itself, demonstrating some movements within VR. Both trainees later found the Oculus Quest 3 with pass-through mode more comfortable due to the ability to see the real world as a reference for their positions. However, limited VR usage time and frequent breaks were required due to VR-induced discomfort with controller issues. These findings highlight the challenges faced by users without prior VR experience. The first trainee's case suggests challenges with balance in VR. The second and third trainees' controller struggles emphasize the need for clear instructions and training on VR interaction procedures. The VR training program for users without prior experience should be improved by introducing basic controls and navigation, providing clear instructions, and allowing users to choose between standing and sitting positions. The Oculus Quest 3 with pass-through mode could also enhance user comfort and reduce disorientation, especially for initial VR users. These recommendations aim to make the VR training program more effective and beneficial for all users.

The current study makes several contributions: it adopts design thinking and learning theories, integrates FM with VR functions, and develops a comprehensive user experience evaluation framework. Uniquely, this research applies the 5W analytical technique and combines qualitative and quantitative data to achieve holistic insights. Focusing specifically on warehouse safety training, it elucidates how VR can support training efforts to prevent workplace accidents, improve operational productivity, and cut operational costs. These findings

provide actionable practical guidance for deploying VR-based safety training within warehouse settings.

5. Limitations

The study's sample, limited to 52 participants from three safety centers, may restrict generalization to diverse warehouse types, such as automated versus manual facilities, which differ in operational complexity and safety requirements. Additionally, the dropout rate, like the three cases excluded due to incomplete data, primarily from motion sickness or scheduling conflicts, may introduce bias, such as over-representing participants tolerant to VR, potentially inflating positive usability and sickness scores, and underestimating real-world challenges for sensitive users. Furthermore, the high proportion of bachelor's degree holders (86.5%) and geographical concentration may limit result generalization, as it may not reflect the educational diversity or global variations in warehouse practices, potentially overestimating VR's feasibility in less educated or culturally different contexts.

From a technological perspective, the VR training scenarios emphasized single-user, task-oriented interactions under controlled conditions. As such, extreme or dynamic environmental conditions like emergency situations, low visibility, time pressure, or compound hazards were not simulated. In addition, multi-person collaborative safety scenarios, such as coordinated forklift operations or team-based emergency responses, were not included. These design choices enhanced experimental control and usability but may limit validity for complex environments.

Additionally, cultural variations in safety practices across global contexts may limit the applicability of findings, as the study was conducted in a single cultural setting. The short-term nature of the study also precluded assessment of long-term learning outcomes, such as the retention of safety skills over time. Furthermore, the absence of a control group, due to logistical and resource constraints, limits the strength of conclusions by preventing direct comparisons of VR training's superiority or comparability to conventional methods, such as classroom lectures or on-site demonstrations.

Regarding cognitive load, individual differences among participants — such as age, prior VR experience, and familiarity with safety procedures — may have influenced perceived mental effort. Participants with limited VR exposure may have experienced higher extraneous cognitive load due to interface learning demands, whereas experienced users may have allocated cognitive resources more efficiently. These factors were not explicitly controlled or stratified in the present study and should be considered as potential confounding variables.

These constraints are acknowledged as limitations, though the exploratory mixed-methods design and post-training assessments (SUS, PQ, cognitive load, SSQ) provided robust within-subject insights into usability, presence, cognitive load, and simulator sickness. Future studies with larger, more diverse samples, including control groups for comparative evaluations (e.g., VR vs. classroom or on-site training), and longitudinal designs could enhance generalization and build on the feasibility evidence established here.

6. Conclusions

This research designs and evaluates user experience to develop a VR application for safety training in warehouses. The study establishes actionable implementation methodologies grounded in design thinking—a user-centered approach that supports divergent thinking to generate innovative ideas. Additionally, this research includes the concept of learning-by-doing. With this method, learners actively practise safety procedures and acquire knowledge through hands-on operation. The findings support the integration of VR technology for safety training in warehouses, with an emphasis on the application of facility management. The study used a mixed-methods approach to assess training

needs along with user experience and positive and negative aspects of VR for safety training in warehouses. Data collection combined qualitative evidence from interviews with 12 safety trainers and experts and quantitative data gathered via questionnaires from 52 safety trainees, with the 5W framework deployed to organise the investigation.

Qualitative analysis via 5W interviews was utilized in this study to develop VR safety training for warehouse environments. This approach was used to illustrate user and training needs and emphasized the importance of the empathy phase from various perspectives. Pre-design interviews supported the strengths of FM and VR's immersive training. The significance of warehouse safety was emphasized given the high accident rates and high-risk severity. The development needs of the VR training application, which focused on end users and safety procedures, were dictated by these findings. The result reveals that training in warehouses is important in preventing accidents, enhancing productivity, and reducing costs related to lost time and unsafe conditions. The 5W approach identifies the root causes of safety issues and aligns the VR training with actual needs, thereby enhancing its impact and relevance in VR safety training, especially for warehouses. Additionally, the 5W reveals the need for further user experience evaluation to ensure its success.

On the other hand, quantitative results from four evaluation methods assessed the user experience of the VR application. Including usability testing to determine how easy it was to use, presence questionnaires to determine the way it felt to be in a VR environment, cognitive load tests to measure mental load and effort, and motion sickness surveys to ensure user comfort. The quantitative analysis through questionnaires from trainees revealed that the VR safety training application demonstrated high usability, indicating a satisfying user experience. The presence level revealed a high sense of involvement, indicating that the VR application effectively immersed the users in the simulated warehouse and increased their sense of interaction and navigation with the training content. The VR warehouse safety training application, according to study results, has a moderate cognitive load in terms of mental load and mental effort, indicating areas for improvement in how individuals manage cognitive overload. According to the motion sickness data, trainees typically reported limited oculomotor and nausea, but no disorientation occurred during the VR application usage.

To translate these findings into practical applications, warehouses can implement VR safety training by adopting scalable hardware solutions such as standalone VR headsets and integrating training modules with existing facility management systems to simulate realistic hazard scenarios. Key steps include providing trainer support for VR setup, ensuring regular updates to training content based on user feedback, and prioritizing scenarios that address high-risk tasks, such as forklift operation or chemical handling, to enhance hazard recognition and compliance. For a smooth transition from feasibility to adoption, managers should follow a phased strategy: first, assess training needs through surveys and incident reviews to identify skill gaps; second, pilot VR modules alongside traditional methods to gather feedback and refine content; third, prepare trainers with hands-on sessions on VR operation and facilitation to ensure effective delivery. Conduct a cost-benefit analysis to quantify the return on investment for VR hardware and development against the cost savings stemming from fewer accidents, reduced downtime, and lower insurance premiums. Finally, integrate VR with existing safety protocols by mapping simulations to real procedures, ensuring IT compatibility, and linking performance data to HR systems for ongoing evaluation.

Despite its promise, VR training faces limitations, including high initial costs for development, accessibility challenges for smaller warehouses, and the need for more realistic VR scenarios to reflect diverse warehouse environments. Additionally, as highlighted in the Limitations section, the lack of a control group restricts conclusions on VR's comparative effectiveness against traditional methods. Future improvements should focus on cost-effective solutions, such as cloud-based VR platforms, and longitudinal studies to assess long-term training impacts,

as noted in the Limitations section, to further validate VR's efficacy in diverse settings. Specifically, future research should incorporate controlled comparisons, such as VR versus classroom or on-site training, to demonstrate relative superiority and guide broader adoption.

In conclusion, this study establishes actionable methodologies and design frameworks via practical implementation. By investigating training requirements and user needs as well as evaluating user experience for warehouse VR safety training, this work delivers an in-depth understanding of the benefits and challenges of applying VR technology to safety training. The findings provide practical references for safety trainers, researchers and enterprises. The results indicate that VR is used as a safety training tool for warehouses and other similar environments. However, the research results and methods in this study can be used for future research to create new applications that cover various types of risks in VR or other industrial environments. Training programs that take user experience factors into account, along with making use of VR's advantages, can be created to improve trainee comprehension and critical thinking abilities and eventually establish safety standards in the organization.

7. Future work

Following the research results, future comprehensive studies with higher sample sizes are needed to uncover more information about the important design and assessment factors for VR safety training simulations. These findings can then be discussed by trainers and experts to customize their training in various fields from different aspects. Creating a customized VR environment for different types of warehouse industries emphasizes the importance of making trainees feel like they are in a real warehouse environment with various types of risks. This preparation ensures readiness for real situations and emergency procedures. Additionally, further investigations can emphasize the way VR may enhance spatial reasoning abilities and motivate learners to identify hazards. Further research can highlight challenges like incomplete risk coverage and the need for voice instructions along with the integration of advanced haptic feedback.

To enhance practical applicability, future VR training scenarios should be explicitly designed around real warehouse operational needs, such as forklift-pedestrian interaction zones, high-density picking areas, loading and unloading docks, and manual material handling tasks. These scenarios can support targeted training for common accident-prone activities, enabling workers to practice risk recognition and safe decision-making under realistic operational constraints.

Future work should extend scenario realism by incorporating extreme and dynamic conditions, such as emergency evacuations, equipment failures, low-visibility environments, and time-critical decision-making tasks. In addition, the development of multi-user VR environments would enable the investigation of collaborative safety behaviors, communication effectiveness, and team-based risk management in warehouses. Furthermore, operations can be integrated, and safety can be improved by using VR to test and improve warehouse designs, traffic flow, and equipment placement before practical implementation by using, for instance, digital twins. Because VR training is dynamic and flexible, it enables continuous commitment to facility management. A sustainable training process appears to be practical by simply updating to reflect modifications to the equipment introduction, procedures, or warehouse layout. Future research should further explore the integration of VR-based digital twins with warehouse management and safety systems, allowing safety managers to simulate layout changes, evaluate traffic flow efficiency, and identify potential hazard zones before physical deployment.

To better understand cognitive load variability, future studies should stratify participants by age, prior VR experience, and professional background, or employ adaptive VR interfaces that adjust task complexity based on user performance. The integration of objective measures, such as physiological indicators, could further complement self-reported

cognitive load assessments. It is essential to remember, though, that trainees might develop erroneous assumptions about real warehouse layouts, so it is imperative to have broad channels of communication regarding the objectives and constraints of VR simulations.

To address generalizability and long-term effectiveness, future research should evaluate the VR safety training application across diverse warehouse types, including automated facilities with advanced robotic systems and manual warehouses with varied layouts, ideally using control group comparisons. Cross-cultural studies are needed to examine how differences in regulatory frameworks and safety cultures influence VR training effectiveness across regions. Additionally, longitudinal studies should investigate long-term learning retention and the sustained impact of VR-based safety training on workplace safety outcomes, such as near-miss frequency and accident rates, to validate its real-world applicability across global warehouse settings.

CRedit authorship contribution statement

Abdallah Al-Hamad: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Mária Csernoch:** Writing – review & editing. **Attila Gilányi:** Writing – review & editing, Writing – original draft, Supervision, Software, Methodology, Investigation, Data curation, Conceptualization.

Declaration of competing 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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Appendix A. Supporting information

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Data availability

Data will be made available on request.

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