

REVIEW

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Virtual reality training programs in disaster preparedness: a systematic review

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Abstract

Background The demand for effective disaster preparedness training in hospitals is steadily increasing, as healthcare staff need to handle emergencies efficiently while providing patient care. However, conventional training methods like live drills and tabletop exercises can require significant resources, limit participation, and disrupt hospital operations. In light of these challenges, Virtual Reality (VR) training has emerged as a modern solution, offering an innovative way to improve training efficiency without interfering with routine hospital activities. This study, therefore, examines how VR training compares to traditional methods in preparing hospital personnel for disasters, focusing specifically on effectiveness and cost.

Methods We reviewed studies concerning the effectiveness and economic assessments of VR compared to traditional methods. To answer the research questions, we followed the Canada Drug Agency's guides on conducting a health technology assessment. Articles were identified from both peer-reviewed and gray literature.

Results The review highlights eight pertinent studies demonstrating VR's advantages, including boosting knowledge retention, performance, and overall confidence among healthcare professionals in disaster preparedness. Furthermore, the economic analysis indicates that although the initial costs of VR synchronous training may be higher, the long-term savings from reduced ongoing training and maintenance can lead to greater cost efficiency. In addition, while VR training presents safety benefits, challenges such as cybersickness and accessibility concerns have also been observed.

Conclusion VR training offers considerable advantages over traditional disaster preparedness methods and significantly improves healthcare workers' confidence and skills. Despite the high upfront costs, the potential long-term financial benefits appear promising. To maximize results, funding for VR initiatives must emphasize demonstrated effectiveness alongside ongoing research to explore broader applications and address the challenges posed by these emerging technologies.

Keywords Virtual reality, Disaster preparedness, Cost-effectiveness



1 Introduction

Disaster preparation exercises are crucial for ensuring that hospital personnel are equipped to respond effectively to emergencies [1]. The cornerstone of these preparatory exercises is to transfer skills to identify hazards and vulnerabilities, which informs the development of comprehensive preparedness plans [1]. These emergency preparedness trainings are very important and often required for accreditation purposes in healthcare settings. For example, all accredited hospitals in Canada must conduct periodic disaster preparation training, including training for managing violent patients, “code white.” These exercises focus on the most likely events, emphasizing areas for improvement and corrective actions [1]. In some cases, the high-risk scenarios may require complex responses, necessitating a variety of training exercises that are repeated periodically [2]. Traditional disaster training exercises can take various forms, ranging from discussion-based, tabletop, drills, and functional to full-scale exercises and practical demonstrations [3]. However, they face limited participation and resource intensity, which can restrict the learning experience and interfere with patient care [3, 4]. Most disaster preparation formats allow only a limited number of participants and may take months to train all hospital staff. New guidelines may be in place or introduced, necessitating that all staff are trained, creating a never-ending need to train and retrain staff. To make matters worse, patient care is significantly disrupted every time staff members are withdrawn from their duties to engage in such training [3].

Virtual reality (VR) revolutionizes training by offering a versatile platform that simulates, customizes, and captures performance data across various scenarios [5]. This technology is particularly effective in replicating dangerous or logistically challenging situations that are difficult to recreate in real life [3, 5, 6]. VR scenarios provide immersive experiences of clinical scenes and contexts, closely mimicking real-world encounters to enhance users’ proficiency and adaptive responses [3, 6]. These virtual environments are designed to help healthcare providers develop essential skills for optimal patient care. By engaging in these VR trainings experiences, users can refine their abilities to manage tasks and challenges while ensuring safety, effective transfer of skills, and overall well-being [6]. VR through its ability to address the limitations of traditional training methods, offers hope for a more effective and efficient future in disaster preparation. It enables many participants to train asynchronously over extended periods, thus maximizing engagement and learning opportunities [3, 5, 6].

Recently, some organizations have begun using VR programs for disaster preparation, a rapidly spreading technology increasingly utilized in education [6]. The uptake of this new technology has significant budget implications since traditional methods are still used concurrently. Moreover, regulatory standards concerning disaster preparation across multiple locations globally still require conventional training methods [7]. Therefore, it is essential to gather evidence to support the implementation of VR training programs and ensure the collection of reliable data to guide further development and enhancement of the training. To inform funding decisions for VR training programs for hospital workers regarding different aspects of emergencies, and evacuation scenarios, comprehensive evidence is needed on the comparative effectiveness, safety, cost, cost-effectiveness, acceptability, social impact, ethics, and educational outcomes of VR training versus traditional methods. This evidence is crucial for decision-makers to determine whether VR training should be funded as a standard hospital training method

for emergency responses or not. A critical assessment is necessary to synthesis available evidence, considering VR's significant budget implications and rapid diffusion. Therefore, this study aims to answer the following question: How does VR training compare to traditional methods (e.g., live demonstrations, use of manikins, discussion-based, table-top drills, online classes) regarding effectiveness, cost, and other relevant outcomes (preparedness, knowledge improvement, confidence, safety, acceptability, social impact, and ethics) for hospital workers in disaster preparedness scenarios?

1.1 Review objectives

- 1) To evaluate the effectiveness of VR training compared to traditional methods in improving healthcare workers' knowledge, self-efficacy/confidence, performance, and satisfaction when it comes to disaster preparedness.
- 2) To evaluate the cost-effectiveness of VR training compared to traditional training methods.
- 3) To review VR safety, acceptance, social impact, and ethical issues.
- 4) To make recommendations regarding embracing and funding VR based on the evidence gathered.

2 Methods

To answer the research question, we conducted three independent reviews, starting with a review of effectiveness, then the economic costs, and finally, an overview of VR's safety, ethics, and social impact.

2.1 Review on VR effectiveness

2.1.1 Literature search and search strategy

The literature search for studies assessing the effectiveness of VR followed the Canada Drug Agency's PRESS (Peer Review of Electronic Search Strategies) checklist [8]. Initially, we identified relevant keywords and MeSH terms by exploring three seed papers [3, 6, 9], focusing on healthcare professionals, virtual reality, preparedness evacuation, and training. We developed a search strategy using these terms based on the PICOS (Population, Intervention, Comparator, Outcome, and setting) framework (Supplementary Table 1). In addition, we used the Canada Drug Agency (CDA) developed search filters to limit retrieval to RCTs, comparative studies, or controlled clinical trials. We searched several databases, including MEDLINE via Ovid, Embase via Ovid, Web of Science, CINAHL, and ProQuest, conducting each Ovid search separately for thoroughness (Supplementary Table 2). The grey literature search was done using Google Scholar, the CDA website, and ProQuest for dissertations. Additionally, we searched clinical trial registries such as the US National Institutes of Health's clinicaltrials.gov, WHO's International Clinical Trials Registry Platform (ICTRP) search portal, Health Canada's Clinical Trials Database, and the European Union Clinical Trials Register. The initial search was completed on October 29, 2024, and regular alerts were set up to update the database searches until November 30, 2024. The search results were exported to Covidence for analysis and duplicate removal. Additional searches for eligible articles were made from the references of the seed papers, the only systematic review related to the research question [6], and references of the articles selected after the final screening.

2.1.2 Article selection criteria

The retrieval was unrestricted by publication date or geography but limited to English-language publications. To ensure comprehensive coverage, we utilized a wide range of peer-reviewed sources, including conference abstracts and dissertations. The study designs included comparative observational studies, quasi-experimental studies, and randomized controlled trials (RCTs). Articles were screened by title and abstract first to determine if they met the inclusion and exclusion criteria; then, the selected articles were downloaded, and a full manuscript screening was conducted. Those that met the criteria were considered for data extraction and quality assessment.

2.1.3 Quality assessment

To ensure the reliability and validity of the studies included in this systematic review, we conducted a comprehensive quality assessment using the ROBINS-I tool for non-randomized studies of interventions (NRSI) and the RoB 2 tool for randomized controlled trials (RCTs). The evaluation was done based on the Cochrane Handbook. The RoB 2 tool evaluated five key domains of bias in RCTs, while the ROBINS-I tool assessed seven domains of bias in NRSI. Data on study characteristics, interventions, outcomes, and risk of bias assessments were extracted using Covidence.

2.1.4 Data extraction strategy

Data extraction was conducted using Covidence, adhering to the PICO framework. We also captured detailed information on study characteristics, such as the first author, year of publication, country, sample size, and study design. For the population, we recorded the type of healthcare professionals involved, the type of disaster being prepared for, and the age and gender of the participants. For the intervention, we documented the description of the virtual reality training, and the number of participants involved. In the control group, we noted the traditional training methods used and the number of participants involved. For outcomes, we captured performance in disaster preparedness tests, confidence/self-efficacy, satisfaction, adverse events, statistical differences, measures of the different outcomes, and the assessor of the outcomes.

2.1.5 Data analysis

The results were presented in a narrative description based on the outcomes. The risk of bias for each study was summarized and presented in tables. The impact of the risk of bias was considered during the interpretation of the findings to ensure that studies with a higher risk of bias did not skew the overall conclusion. This final report analysis only includes studies that meet the selection criteria and were identified before the stakeholder feedback period. Any studies identified after this period were discussed and compared to the initial analysis.

2.2 Economic review

2.2.1 Search strategy and article selection

The literature search was similar to the clinical review search (same databases); we maintained the search string for the population, intervention, and study design. However, we added a search string to identify economic evaluation studies. See the last row of Supplementary Table 1. To broaden the search for economic assessment studies, additional

databases such as the Scottish Intercollegiate Guidelines Network (SIGN), Database of Abstracts of Reviews of Effects (DARE), and NHS Economic Evaluation Database (NHS EED) were searched. The detailed search string is present in Supplementary Table 3. The identified articles were exported to Covidence software. Within Covidence, the same article selection process was followed. The included studies were related to economic evaluation, comparing VR to other traditional means of disaster preparation.

2.2.2 Data extraction, quality assessment, and data analysis

The articles that met the inclusion criteria were rigorously assessed for their reporting accuracy using the CHEER-2 checklist, ensuring comprehensive and transparent reporting of economic evaluations [10]. Detailed information was meticulously extracted from each article, covering several key aspects. For article characteristics, we noted the first author, year of publication, country, and currency used. The population section detailed the specific types of healthcare workers. We provided comprehensive details about the virtual reality training program for the intervention and the comparator. In the economic evaluation, we documented the horizon and perspective of the analysis, as well as detailed cost data of the VR training compared to traditional methods. As for the clinical review, a narrative description of the results was done in this analysis.

2.3 An overview of literature comparing VR and traditional methods in disaster preparedness skilling regarding safety, accessibility, social impact, and ethics

To ensure we review all aspects potentially needed to make an appropriate recommendation, we reviewed safety, accessibility, social impact, and ethics using a rapid review. We used Google Scholar to gather information related to the topics.

3 Results

3.1 Review on VR effectiveness

A total of 445 articles were identified from various sources. After removing 75 duplicates, 370 unique articles remained. During the initial screening of titles and abstracts, 352 articles were deemed irrelevant, leaving 18 articles for full-text review. Following this thorough review, data collection and quality assessment were conducted on the eight articles that met the inclusion criteria (Fig. 1). Almost all studies from the previous review mainly described virtual environments but were not necessarily immersive [characteristic virtual reality procedure] [6], and only 1 study was included from the prior review.

3.1.1 Study characteristics

The included studies were published between 2010 and 2022. At the same time, the sample size ranged between 15 and 197 individuals. The majority of the samples between the intervention and comparator were evenly divided. Two were RCTs [11, 12], and the rest were NRCTs—most of which were quasi-experimental studies ($n=4$) [9, 13–15]. Most of the studies were conducted in the USA ($n=6$), with the remaining studies from China ($n=2$). Most participants were nurses. Most VR programs were compared to traditional or standard practice methods for preparing individuals for disaster. The studies included various disaster preparedness scenarios, such as neonate evacuation, disaster drills, OR

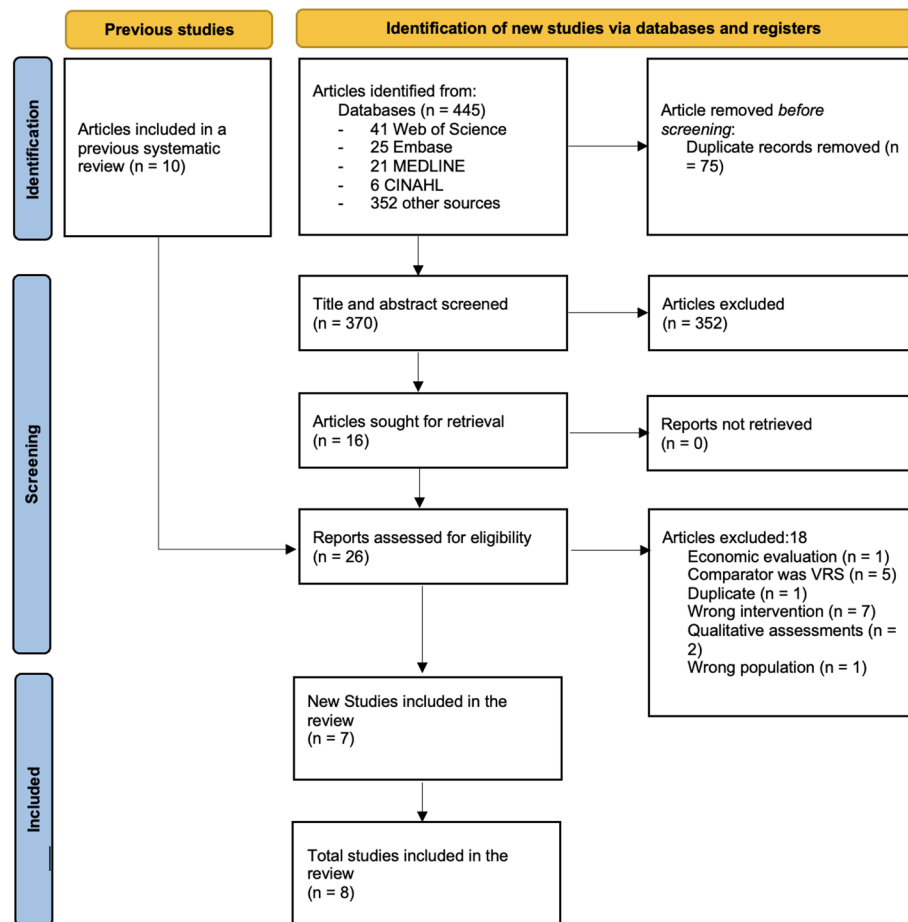


Fig. 1 PRISMA flow diagram for the clinical review involving Virtual reality effectiveness in disaster preparedness

fire safety, disaster preparedness, nursing skills, and decontamination procedures. For further details, refer to Table 1.

3.1.2 Quality assessment of the selected studies

The risk of bias assessment for the RCTs consistently shows low risk across all domains [11, 12] (Supplementary Table 4).

In contrast, the NRCTs exhibit more variability. Four NRCT studies had a moderate risk due to confounding [13–15]. Participant selection presents a moderate risk of bias for two NRCTs [16, 17]. All studies consistently show low risk in intervention classification, deviations from intended interventions, outcome measurement, and result selection, except for Rossler et al., which has a moderate risk due to missing data [16] (Supplementary Table 5).

Overall, RCTs had a low risk of bias, while NRCTs vary, particularly in confounding and participant selection. Supplementary Table 6 details each study's assessment.

The studies reviewed highlighted several limitations that could impact the generalizability and reliability of their findings. Common limitations included small sample sizes, which reduce the statistical power and the ability to generalize results to larger populations [9, 11, 16, 17]. Many studies relied on self-reported measures, introducing potential biases and inaccuracies in the data [9, 13–15, 17, 18]. The lack of randomization in

Table 1 Study characteristics of studies assessing virtual reality effectiveness in disaster preparedness

Study	Design	Population	Sample Size	Country	Age	VR description (n)	Comparator description (n)	Disaster preparedness drill or procedure description	Outcome
Farra et al. 2018 [9]	Quasi-experimental	NICU workers	93 (initial), 62 (final)	USA	25–31 years (majority)	Four VRS scenarios for neonate evacuation training (62)	Web-based clinical updates (62)	Neonate evacuation	Knowledge, confidence, performance
Pamela et al. 2010 [11]	Randomized trial	EM residents	15	USA	PGY 1–4 residents	Full-immersion VR disaster drill	Standardized patient (SP) drill	Mass casualty triage	Knowledge, triage performance, post-test results
Rossler et al. 2019 [16]	Experimental pretest-post-test design	Prelicensure nursing students	20	USA		Virtual Electrosurgery Skill Trainer (VEST) for OR fire safety skills	Traditional programmatic education	OR fire safety	Knowledge, skills acquisition
Liao et al. 2022 [12]	Randomized controlled trial	Nursing students	101	China	Average age 20.6 ± 0.9 years	VR training scenarios for disaster preparedness (49)	Traditional disaster nursing course (52)	Disaster preparedness	Disaster preparedness, confidence, performance
Smith et al. 2020 [13]	Quasi-experimental design	Senior nursing students	121	USA	Primarily young adults	VR simulation for nursing skills training (61)	Traditional training methods (60)	Nursing skills in decontamination	Performance, satisfaction, self-confidence
Smith et al. 2018 [15]	Quasi-experimental design	Senior baccalaureate nursing students	197	USA	Primarily young adults	VR simulation for decontamination skill (117)	Written instructions for decontamination skill (55)	Decontamination	Cognitive learning, performance, performance time
Smith et al. 2016 [14]	Quasi-experimental design	Senior baccalaureate nursing students	108	USA	Primarily young adults	VR simulation for decontamination skill (57)	Written instructions for decontamination skill (51)	Decontamination	Cognitive knowledge, performance, performance time
Zhao et al. 2022 [17]	Comparative study	Operating room nurses	60	China	Average age 28.20 ± 0.96 (control), 29.57 ± 1.04 (experimental)	VR training for operating room procedures (30)	Traditional training methods (30)	Operating room procedures	Examination results, learning enthusiasm, training effect, satisfaction

some studies further limits the ability to draw causal inferences [13–15]. Additionally, several studies were conducted within single institutions or universities, which may not represent broader settings. The absence of long-term follow-up in the studies also means that the sustainability of the observed effects remains to be determined (Supplementary Table 7).

3.1.3 Effective of virtual reality in disaster preparedness

Overall, VR training enhances knowledge, performance, confidence, and satisfaction. For details, see Table 2.

3.1.3.1 Knowledge Cognitive assessment and test scores were used to measure knowledge. Smith et al. showed significant Knowledge improvement [14], while Farra et al. and Rossler et al. did not find significant differences but acknowledged VR's potential for education [9, 16].

3.1.3.2 Performance Performance was assessed through various measures, including examination of live demonstrations with exercise examinations and checklists in the presence of examiners. Four studies reported significant performance improvement [9, 14, 17, 18], and two found VR as effective as traditional methods [13, 15].

3.1.3.3 Confidence Confidence was measured using self-efficacy questionnaires and self-development assessment cards; the two studies that measured confidence showed different findings, with one demonstrating no difference in self-efficacy [9] and the other significantly improving it using VR in disaster preparedness [18].

3.1.3.4 Training and learning satisfaction Satisfaction was measured using questionnaires. Zhao et al. reported significant improvements ($P < .05$), highlighting VR's positive reception [17].

3.1.4 Adverse events

None of the studies reported any adverse event related to VR use or other traditional teaching methods (Appendix 4).

3.2 Economic review

Twelve articles were identified from various databases. After removing two duplicates, ten unique articles remained. The abstracts and titles of these articles were screened for eligibility, and two articles met the criteria. Following a full-text review, only one article was deemed eligible for data extraction (Fig. 2).

The economic evaluation study by Ferra et al. [3] examined the cost-effectiveness of VR training compared to traditional live drills for healthcare workers in the United States. Involving nurses, respiratory therapists, and monitor technicians, the study employed VR technology to simulate various evacuation scenarios through an interactive story. For three years, training sessions occurred every three months and lasted around 15 min. The comparison involved hands-on drills using mannequin infants, following Department of Homeland Security guidelines and focusing on evacuating neonatal mannequins from a NICU setting. Analyzing costs from the hospital's perspective,

Table 2 Effective of virtual reality in disaster preparedness

Article	Effect Size / P-values	Comment about Effectiveness of VR	Outcome Measurement
Knowledge			
Farra et al. 2018 [9]	No statistical difference	VRS is as effective as traditional methods in promoting positive performance outcomes	Cognitive assessment scores
Rossler et al. 2019 [16]	No significant findings	VR simulation may be considered to teach fire safety education or reinforce general fire safety practices to nursing students and novice nurses.	Cognitive assessment scores
Smith et al. 2016 [14]	Significant improvements in cognitive test scores	VRS is at least as good as traditional methods and superior in some cases for retention of knowledge and performance of skills.	Cognitive test scores
Performance			
Farra et al. 2018 [9]	Significant improvements ($P < .0001$, effect size 1.71)	VRS is effective in promoting positive performance outcomes	Performance in live evacuation exercises
Liao et al. 2022 [18]	Significant improvements ($F(1,94) = 4.298$, $p = .041$, $\eta^2 = 0.044$)	VR enhances disaster preparedness performance among nursing students.	Performance assessment by examiners
Smith et al. 2020 [13]	No significant differences	VR is as effective as mannequin-based simulation for training in disaster skills.	Decontamination Checklist
Smith et al. 2018 [15]	No significant differences	VRS provides an alternative for simulated learning experiences.	Decontamination Checklist
Smith et al. 2016 [14]	Significant improvements in performance	VRS is at least as good as traditional methods and superior in some cases for retention of knowledge and performance of skills.	Performance rubric scores and task completion time
Zhao et al. 2022 [17]	Significant improvements ($P < .05$)	VR improves training performance in nuclear radiation emergency medical rescue.	Examination results, training effect evaluation
Confidence			
Farra et al. 2018 [9]	No significant finding	VRS is as effective as traditional methods in improving confidence	Self-efficacy questionnaire
Liao et al. 2022 [18]	Significant improvements ($F(1,94) = 6.992$, $p = .010$, $\eta^2 = 0.069$)	VR enhances confidence in disaster preparedness among nursing students.	Self-developed assessment cards
Training and learning Satisfaction			
Zhao et al. 2022 [17]	$P < .05$	VR improves training satisfaction in nuclear radiation emergency medical rescue.	Satisfaction questionnaire

live exercises incurred total expenses of \$18,617.54 for 57 participants, which projects to \$76,750.02 annually for 334 staff. Meanwhile, the development costs for VR training amounted to \$106,951.14, with projected expenses of \$115,659.92 over three years for the same number of staff. VR training proved increasingly cost-effective, with a per-participant cost of \$115.43 versus \$229.79 for live exercises. For live drills, costs included planning and design fees totalling \$7,184.10 for 160 staff hours, covering ten one-hour planning meetings. Implementation costs comprised participant hours (\$2,726.42), support staff hours (\$5,021.88), and evaluator hours (\$3,685.14), totalling \$18,617.54, leading to annual training costs of \$76,750.02 for all 334 NICU staff. In contrast, VR training's development expenses included storyboard creation (\$6,000), content creation (\$79,524), and external review (\$10,000), totalling \$106,951.14. Implementation costs for VR training included participant hours (\$294.14) and additional costs for hardware and maintenance. Annual costs for VR training were minimal, amounting to \$3,090.97 for training all 334 NICU staff.

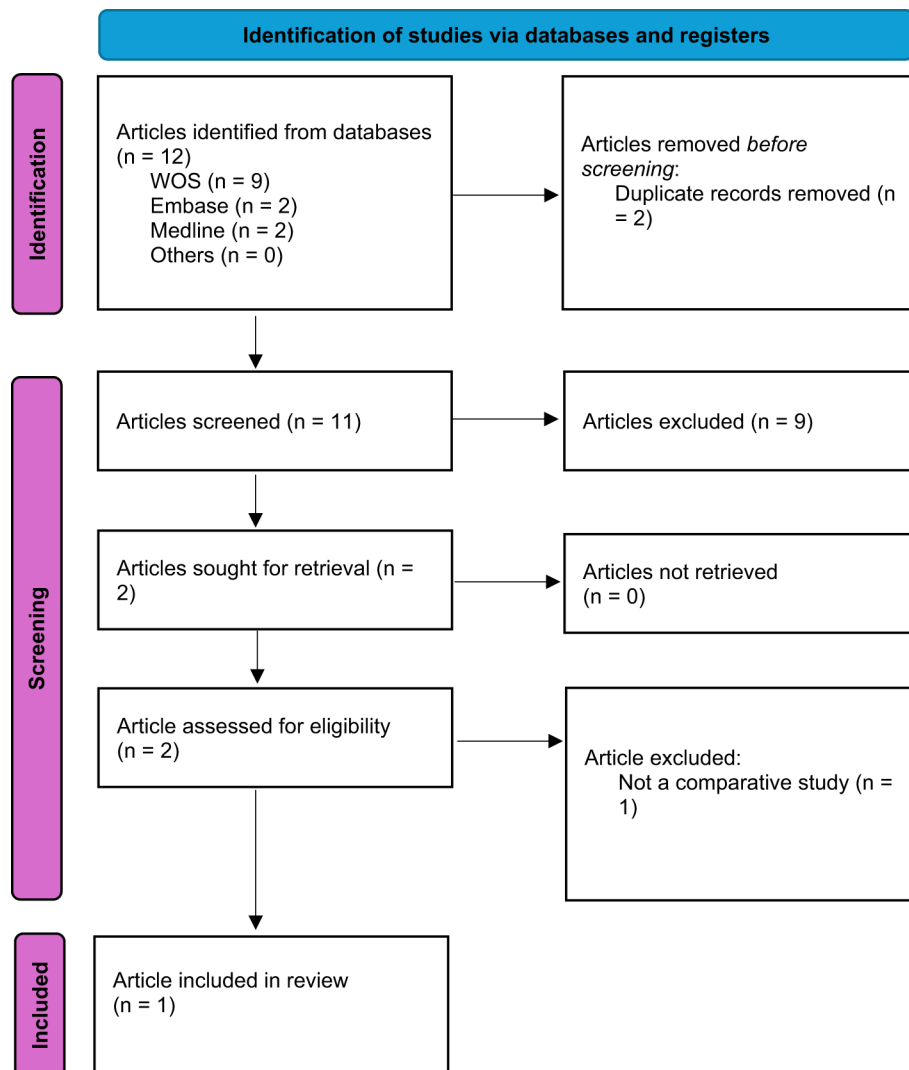


Fig. 2 PRISMA flow diagram for the economic evaluation review involving virtual reality in disaster preparedness

3.3 Overview: comparing VR and traditional methods in disaster preparedness skilling regarding safety, accessibility, social impact, and ethics

3.3.1 Safety

While VR offers significant safety advantages by providing a controlled environment for disaster preparedness training, it also presents unique challenges. Prolonged use of VR can lead to physical health issues such as eye strain, headaches, and “cybersickness,” which includes symptoms like nausea and dizziness [19]. Additionally, VR can cause mental health issues, including depersonalization and derealization disorders, where users feel detached from their thoughts and surroundings [20]. There is also a risk of exacerbating PTSD symptoms in some individuals. The traumatic events the individuals are exposed to during exposure to the scenarios may be traumatic enough to induce PTSD. While involving real-world risks, traditional methods do not typically induce such side effects. Other safety concerns include spatial tracking challenges and safety protocols for unsupervised use, which significantly impact real-world implementation. Some individuals end up getting physically hurt by environmental objects, creating a need for a chaperone when participating in VR exercises.

3.3.2 Accessibility

Accessibility remains a significant challenge for VR in disaster preparedness training. Despite the decreasing costs of VR equipment, the initial investment can still be prohibitive for many organizations, particularly in resource-limited settings. Furthermore, VR systems often require physical movement, which can be challenging for individuals with disabilities [21]. Traditional methods, on the other hand, usually rely on more readily available resources and do not require specialized technical knowledge.

3.3.3 Social impact

The social impact of VR in disaster preparedness training is multifaceted. While VR can enhance teamwork and communication skills through collaborative scenarios, it may also lead to social isolation if not implemented thoughtfully [22]. VR's immersive nature can reduce face-to-face interactions, which is crucial for building strong team dynamics in real-world settings. Additionally, the shift to VR training could lead to unemployment for individuals whose careers are dedicated to traditional training methods.

3.3.4 Ethics

Ethical considerations in VR training are paramount. One of the primary ethical challenges is ensuring that VR scenarios do not cause undue psychological stress or trauma to participants [20]. The realism of VR can sometimes lead to intense emotional responses, which need to be carefully managed. Privacy concerns are also significant, as VR can collect extensive personal data, raising issues about data security and user privacy [23]. Developers and designers must consider the ethical implications of their creations, including the impact on users' mental and physical well-being. While not immune to moral issues, traditional methods generally do not involve the same level of data collection and privacy concerns.

4 Discussion

4.1 Clinical review

Integrating VR in healthcare professional's training has shown promising results across various domains, enhancing confidence, performance, knowledge acquisition, and user satisfaction. This discussion synthesizes findings from recent peer-reviewed literature on disaster preparedness training to provide a comprehensive overview of VR's impact in these areas as highlighted below.

4.1.1 Confidence and self-efficacy

Multiple review studies have consistently demonstrated that VR training significantly improves participants' confidence and self-efficacy [24–28]. For instance, a scoping review by Kouijzer et al. highlighted that VR interventions in healthcare settings enhance users' confidence by providing immersive and interactive experiences that traditional methods lack [24]. This improvement in confidence is crucial for healthcare professionals, as it directly influences their ability to perform under pressure and make critical decisions. With VR scenarios becoming more advanced with the incorporation of Artificial intelligence (AI) and the use of big data to demonstrate real-life scenarios, the confidence level among learners who use it will only keep improving [29, 30]. This aspect may not easily be scaled up with traditional methods in disaster preparation.

4.1.2 Performance enhancement

VR has also been shown to be more effective than traditional training methods in enhancing performance, except in specific scenarios such as decontamination. A systematic review by Mergen et al. found that VR training improved performance metrics such as task completion time and accuracy in various medical procedures [31]. It is easier to superimpose the learned skills from VR in real-life situations due to how close they are to the actual disaster scenario. However, in decontamination scenarios, traditional methods still hold an edge, possibly due to the tactile and procedural nuances that VR simulations have yet to replicate fully. In such scenarios, incorporating both VR and traditional methods may be handy. However, no study has demonstrated the benefits of using both methods.

4.1.3 Knowledge acquisition

Regarding knowledge acquisition, VR is as effective as conventional methods, with notable exceptions in decontamination training, where it was statistically better. The review by Mergen et al. also reported that VR significantly improved knowledge retention and understanding in scenarios designed for decontamination [31]. This suggests that VR's immersive nature can enhance learning outcomes by providing realistic and engaging environments that facilitate a more profound understanding and retention of complex procedures.

4.1.4 User satisfaction

User satisfaction is another critical metric where VR outperforms traditional methods. Healthcare workers have markedly preferred VR training due to its interactive and engaging nature. A study by Kouijzer et al. [24] reported that participants found VR training more enjoyable and motivating than conventional methods. This increased satisfaction can lead to higher engagement and better learning outcomes, as users are more likely to participate actively and consistently in training programs. It is also important to note that many individuals are excited about new technology; we hope this excitement continues with VR so that it facilitates better learning.

4.2 Economic evaluation

Limited literature addresses the economic evaluation of VR compared to other traditional methods. However, in the identified study based on this review [3], VR was more expensive during the initial stage of its implementation and development, an aspect related to the cost of the equipment; however, the price over the long time (3 yrs) was lower due to the low maintenance cost and recurring costs. Meanwhile, the cost of traditional methods remained the same year in and year out. The findings in our review are consistent with other economic evaluations of VR; a systematic review by Gómez Bergin and Craven reinforced that VR is more expensive during the initial stages of implementation due to equipment costs; it becomes more cost-effective over time due to lower maintenance and recurring costs [32]. For instance, the cost per gadget has decreased from over 10 K USD in 2016 to less than 500 USD in 2024, a significant decline in the price [33, 34]. Additionally, the costs of developing VR scenarios have been going low [33]; this is further improved by incorporating AI, making scenario development more straightforward and cheaper and making VR a more affordable and scalable solution

[35]. Therefore, equipment costs are decreasing and becoming more affordable, yet technology is improving.

4.3 Overall

These studies underscore VR's potential as a transformative tool in healthcare training, showcasing significant advantages in improving confidence, performance, knowledge acquisition, and user satisfaction. However, challenges exist, such as the high initial cost of VR equipment and the need for standardized evaluation methods. To address these issues, future research should focus on developing cost-effective VR solutions and establishing robust frameworks for assessing the effectiveness of VR training programs.

While traditional methods remain relevant in specific scenarios, VR's overall benefits suggest that it should be increasingly integrated into healthcare education and training programs. Continued research and development in this field will be essential to fully realizing VR's potential to enhance healthcare outcomes.

4.4 Limitations of the current review

The meta-analysis was not feasible due to significant heterogeneity in the results and differences in outcome measures, which complicated the synthesis of findings and limited the ability to draw generalizable conclusions. The overall quality of the included studies was low, with some studies scoring poorly on quality assessments still being included, which may affect the reliability and validity of the conclusions drawn. None of the included studies used a validated tool to assess the outcome variables, thus further limiting the quality of the findings. Furthermore, the wide variety of definitions of virtual reality used in the included studies has led to inconsistencies and difficulties in applying findings to current research. Standardizing the definitions and criteria for VR in future studies will help achieve more comparable and reliable results. Only one economic evaluation was included, which lacked comprehensive concepts and did not cover various aspects commonly reported in the CHEER-2 guidelines (Supplementary file 8), thereby limiting the understanding of the cost-effectiveness of VR interventions. Furthermore, the economic analysis included does not clearly address the curriculum development costs, which are pivotal to the development of the VR educational model. We therefore recommend that future studies employ more robust health economic methodologies and consider essential costs, such as those associated with curriculum development. The economic evaluation included a paper that compared the vastly different aspects of a summative (live exercise) and a formative VR training that did not capture the cost of training development. Lastly, accessibility to VR technology remains limited for individuals with insufficient financial resources, as the high initial costs of VR equipment can be a barrier to widespread adoption, particularly in resource-constrained settings. Efforts to reduce costs are welcome.

5 Conclusion and recommendation for funding

Virtual Reality (VR) has demonstrated significant advantages over traditional methods in disaster preparedness training, particularly in enhancing self-efficacy, performance, and confidence by mimicking real-world scenarios. Additionally, VR has been observed to be more cost-effective in the long run as the technology becomes more affordable and advanced. However, the studies supporting these findings often suffer from

methodological limitations, such as small sample sizes, affecting the results' generalizability. Addressing the challenges related to safety, accessibility, social impact, and ethics is crucial for effectively and ethically implementing VR in disaster preparedness training. Continued research and development will be vital to fully realizing VR's potential to enhance disaster preparedness and response capabilities. Given these considerations, VR funding should be prioritized in scenarios where its effectiveness has been clearly demonstrated. Further research is essential to establish the generalizability and reliability of VR training across diverse settings and populations. Funding a combination of VR and traditional methods is not currently recommended, as there is no substantial evidence supporting the added benefit of such an approach. Ultimately, the decision to fund VR programs should be made at the discretion of hospital administration, taking into account current best practices and evidence-base, the specific needs and resources of the institution.

Supplementary Information

The online version contains supplementary material available at <https://doi.org/10.1007/s44217-025-00771-5>.

Supplementary Material 1

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Author contributions

MMK and ATO were involved in conceptualizing the research idea. MMK and ATO were involved in the literature search process. PA, ATO, and MMK conducted data screening and capturing. MMK drafted the initial manuscript, and GAC, PA, ATO, and DM provided substantial intellectual contributions in the subsequent revisions. ATO supervised the various stages involved in the writing of this current manuscript. ATO and MMK were involved in the visualization of the current manuscript. All authors gave final approval of the version to be published and agreed to be accountable for all aspects of the manuscript work.

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Data availability

No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate

Not applicable since we used open-access data available in the public domain.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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