Virtual Reality for Training Emergency Medical Responders in Mass-Casualty Incidents: Evidence Synthesis and a Hybrid Implementation Framework

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Abstract. Immersive virtual reality (VR) can reproduce rare, hazardous, and logistically demanding emergency scenarios, but its educational advantage over conventional simulation remains uncertain. This structured rapid review evaluates evidence for VR in training and assessing emergency medical responders and health-professions learners, with emphasis on triage, decision-making, stress, retention, and implementation. PubMed was searched on 15 August 2026 for English-language studies published from 2019 onwards. Of 101 records, 31 underwent detailed assessment and 25 met the focused eligibility criteria. Controlled studies showed that VR was often comparable with live or manikin-based simulation and sometimes superior to lecture or written cases for triage accuracy, motivation, or short-term performance. One randomized crossover trial found higher 30-day knowledge retention than video learning, whereas several comparisons found no significant advantage. Observational studies support VR as an objective, repeatable platform for assessing triage, information transfer, and error patterns; stress responses were variable and cannot be assumed to approximate live exercises. Evidence remains heterogeneous, mostly educational, and rarely longitudinal. On this basis, the paper proposes a four-phase hybrid implementation framework that combines frequent VR practice with periodic hands-on and live simulation, explicit decision gates, instructor preparation, accessibility and data safeguards, and retention-focused evaluation. VR is best treated as a scalable complement rather than a replacement for physical simulation.

Keywords: Emergency medical services, Immersive learning, Mass-casualty incident, Simulation-based education, Triage, Virtual reality

1 Introduction

Mass-casualty incidents (MCIs) force emergency personnel to classify and treat many patients while information is incomplete, hazards evolve, and resources are constrained. These events are uncommon enough that experience is difficult to accumulate, yet errors in scene assessment, triage, communication, or hemorrhage control can have im-

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mediate consequences. Live exercises provide physical interaction and interagency realism, but they require actors, equipment, space, facilitators, and careful safety management. Their cost and logistical burden limit repetition.

Immersive virtual reality (VR) addresses a different part of the training problem. A headset-based environment can expose learners repeatedly to standardized casualty patterns, environmental noise, time pressure, and branching decisions while recording actions at event-level resolution. Scenarios can be paused, replayed, and altered without placing patients or trainees in danger. However, immersion is not equivalent to educational effectiveness. Limited haptics, simulator sickness, interface friction, and platform-specific sensory cues may distort performance, and high engagement can be mistaken for durable learning.

Two systematic reviews concluded that VR is promising for disaster and first-responder education, particularly because it supports safe repetition and generally positive learner experience. Both also found substantial heterogeneity, limited long-term follow-up, and insufficient evidence that VR should replace live simulation [1, 2]. The practical decision is therefore not whether VR is universally superior, but which competencies it can support, what evidence should govern adoption, and how it should be combined with physical practice.

This paper updates and narrows the evidence to emergency and disaster scenarios, replaces causal hypotheses with answerable research questions, and contributes an evidence-informed hybrid implementation framework. It asks: (RQ1) What does recent evidence show about VR effects on triage, decision-making, knowledge, retention, and stress? (RQ2) Which limitations and implementation conditions determine whether VR training is usable and safe? (RQ3) How can VR and physical simulation be combined in a staged curriculum with measurable decision gates?

2 Methods

2.1 Design and Search Strategy

A structured rapid evidence review was conducted to support a time-bounded conference synthesis. PubMed was selected as the primary biomedical index, and reference lists of eligible reviews and studies were checked for contextual completeness. The final search was run on 15 August 2026 using the following query: (("virtual reality" OR "immersive virtual reality") AND (training OR education OR simulation) AND (paramedic* OR "emergency medical service" OR "emergency medical services" OR "first responder" OR "first responders" OR "mass casualty" OR triage OR "medical emergency" OR "medical emergencies")) in titles/abstracts, limited to English-language records published from 1 January 2019 to 15 August 2026. The complete query, record identifiers, screening decisions, exclusion reasons, and extraction matrix were archived during preparation.

2.2 Eligibility, Screening, and Extraction

Eligible records examined headset-based immersive VR used to train or assess prehospital responders, emergency clinicians, or health-professions learners performing emergency, triage, disaster, or mass-casualty tasks. Studies had to report objective performance, knowledge, retention, physiological or perceived stress, or implementation findings based on participant data. Systematic or integrative reviews directly addressing disaster or first-responder VR training were also eligible. Patient treatment, rehabilitation, unrelated procedural specialties, non-immersive desktop simulation, purely technical demonstrations, and sources without verifiable publication metadata were excluded.

One reviewer screened titles and abstracts, then performed detailed assessment against the prespecified criteria. The search identified 101 records; 70 were excluded at title/abstract screening and 31 underwent detailed assessment. Six records were excluded at that stage because they concerned virtual-reality applications in other sectors and did not address the implementation of education or training for health professionals; they were therefore not included in the comparative synthesis. Twenty-five records informed the synthesis. Open-access full text was archived for 19 included records. The remaining six—Brown et al. [1], Mills et al. [3], de Visser et al. [15], Lopez Lopez et al. [17], Eide et al. [22], and Wang et al. [25]—were assessed only from indexed abstracts and verified publisher metadata. Their full methods, methodological quality, unreported outcomes, and limitations could not be assessed to the same depth as those of the 19 full-text publications; consequently, only results explicitly reported in the abstracts were used and these six records were interpreted cautiously. Extraction covered population, design, comparator, scenario, outcome type, follow-up, principal result, and limitation.

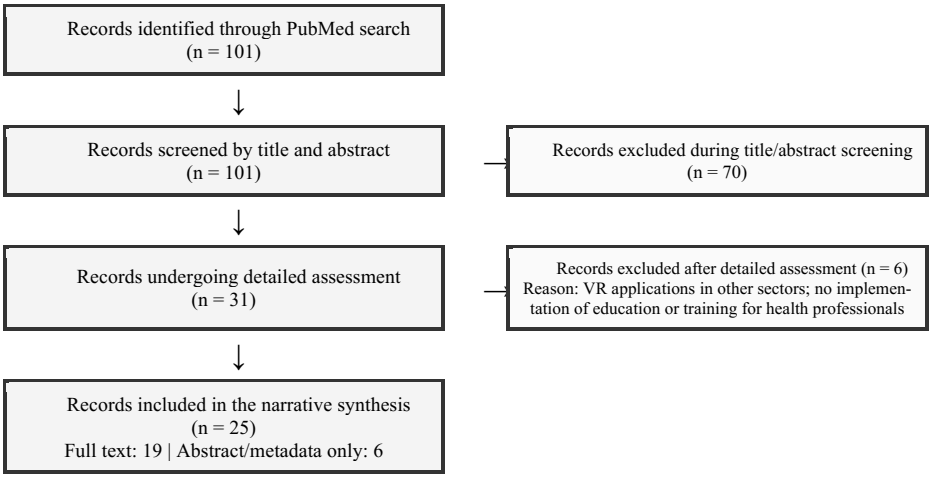


Fig. 1. Study selection process for the structured rapid review.

2.3 Critical Appraisal and Synthesis

Because designs ranged from randomized trials to qualitative studies, a single numerical risk-of-bias score would imply false comparability. Each record was instead appraised across five domains: clarity of population and context, transparency of methods, appropriateness of comparator or analytic frame, objectivity and temporal depth of outcomes, and explicit treatment of uncertainty. Evidence was classified as higher contribution (controlled comparison with objective outcomes), moderate contribution (objective observational or quasi-experimental evidence, or a heterogeneous review), or contextual contribution (qualitative, feasibility, usability, or perception evidence). Findings were synthesized narratively because interventions and endpoints were too heterogeneous for meta-analysis. No participants or identifiable data were involved; ethics approval was therefore not required. Appraisal of the six abstract-only records was necessarily limited and provisional; none was used independently to support a strong causal or generalizable conclusion.

3 Results

3.1 Learning and Performance

The comparative evidence does not support a universal claim that VR is superior. In 29 paramedicine students, Mills et al. found similar triage accuracy, workload dimensions, and satisfaction in VR and live MCI simulation; card allocation was faster in VR, and delivery cost for that specific exercise was approximately one thirteenth of the live scenario [3]. In the multicenter SMARTSIM randomized trial (n = 174), cognitive examination scores did not differ between 3D VR and traditional simulation [4]. A small quasi-experimental START-triage study likewise found no significant knowledge advantage over lecture, although satisfaction favored VR [5].

More recent comparisons identify circumstances in which VR added value. A randomized study of 83 paramedic students found that both approaches improved knowledge, while the VR group showed higher motivation and better SORT-triage accuracy in a live assessment [6]. A non-equivalent controlled study in nursing students reported improvements in triage accuracy and cognitive flexibility relative to written cases [7]. An OSCE-based randomized trial in 46 medical trainees found higher knowledge gain and better MCI performance after a two-hour VR intervention than after lecture [8]. A comparative evaluation of basic rescue training favored VR for several checklist-based skills but not hemorrhage control [9]. These results are encouraging but mainly immediate and education-specific. The populations represented paramedic students, nursing students, and medical trainees; these education-specific results should not be generalized to all emergency medical responders without regard to learner background, professional role, and training context.

Evidence concerning retention is limited and mixed. In a randomized crossover study of 72 senior medical students, short-term knowledge gains after VR with automated feedback and video seminars were similar. At 30 days, retention was higher after VR (75.4% versus 69.0%) [10]. In contrast, a randomized pilot of tourniquet training found no significant difference between VR and instructor-led teaching either immediately or at three months [11]. The defensible conclusion is that VR has produced broadly similar outcomes to established modalities in some comparisons and may improve selected outcomes when scenario design, feedback, and transfer assessment are aligned; superiority or durable retention cannot be presumed from immersion alone.

Table 1. Representative studies with the greatest relevance to effectiveness, assessment, and stress.

Evidence	Design/context	Key result	Appraisal
Mills et al. [3]	Random-order VR/live MCI comparison; n = 29 paramedicine students	Comparable accuracy and satisfaction; faster allocation in VR; scenario-specific cost advantage	Abstract-only; full methodological appraisal unavailable
Donathan et al. [4]	Multicenter randomized VR/traditional simulation trial; n = 174	No difference in median cognitive examination score	Higher; single post-test
Chumvanichaya et al. [6]	Randomized triage-training comparison; n = 83	Both improved knowledge; VR improved motivation and live SORT accuracy	Higher; short, single-site study
Lindner et al. [10]	Randomized crossover VR/video study; n = 72	Similar immediate gains; higher 30-day retention after VR	Higher; two student scenarios
Saggar et al. [11]	Randomized VR/instructor tourniquet pilot; n = 53	No significant difference immediately or at three months	Higher; attrition and one skill
Baetzner et al. [12]	Five VR MCI scenarios; n = 76	Accuracy, speed, and information transfer differentiated expertise	Moderate; assessment, not training comparison
Kman et al. [13]	SALT/hemorrhage assessment; n = 282	Prehospital clinicians were faster and more accurate than trainees	Moderate; cross-sectional
Tovar et al. [14]	Physiological VR MCI study; n = 35	Sympathetic activation occurred, but without a live comparator	Moderate; small heterogeneous sample

Note: Mills et al. [3] was assessed from the indexed abstract and publisher metadata only; its methodological quality and limitations could not be evaluated to the same depth as those of full-text studies.

3.2 Assessment, Error, and Stress

VR appears particularly useful as a standardized assessment environment. Baetzner et al. compared medical first responders with non-first responders across five immersive MCI scenarios. Triage accuracy, speed, and information-transmission efficiency differentiated expertise, whereas the study did not compare VR training with a traditional control [12]. This distinction corrects an important interpretive risk: the study validates candidate performance indicators, not a percentage improvement caused by VR. In a separate cohort of 282 participants, experienced prehospital clinicians outperformed medical trainees in triage accuracy and speed, supporting the simulator's sensitivity to expertise [13]. An error analysis of 99 responders found 70% correct triage and separated proficiency errors from procedural limitations and perceptual errors introduced by smoke, sound, and other programmed cues [15]. A 360-degree pediatric MCI study also demonstrated feasible large-sample assessment, though without a learning comparator [16]. A 2026 military study similarly concluded that VR captured decision and fatigue patterns but did not directly establish improved learning [17]. These studies

enrolled different groups, including medical trainees, experienced prehospital clinicians, emergency responders, and military personnel. Their findings therefore describe performance within specific populations and scenarios and should be generalized to emergency medical responders only with appropriate caution.

Stress findings are neither uniformly beneficial nor interchangeable with live exercise. A 360-degree MCI increased sympathetic activation in 35 medical participants, while subjective stress differed by experience [14]. In a staged military scenario, novelty produced the clearest physiological response; adding nominally stronger stressors did not sustain it [18]. VR can therefore expose trainees to cognitive load and support stress measurement, but claims that it reduces stress or faithfully reproduces operational stress require a matched comparator and repeated exposure. Excessive arousal, cybersickness, and fatigue should be treated as safety and learning variables rather than signs of realism.

3.3 Usability and Implementation Conditions

Presence, usability, and instructional design interact. In a multi-user emergency scenario, perceived presence was associated with perceived effectiveness, while interface limitations and extraneous cognitive load reduced the benefit [19]. A large post-encounter evaluation found high realism ratings and willingness to recommend immersive MCI training, but these were acceptability rather than competence outcomes [20]. Mixed-methods evidence likewise supports repeatability while documenting technical interruptions and physical symptoms [21]. Cross-service responders emphasized that implementation requires reliable infrastructure, realistic cues, stakeholder involvement, and shared protocols [22].

Qualitative evidence clarifies what the technology must serve. Ambulance clinicians used VR to make their clinical reasoning visible and to reflect safely on decisions [23]. First responders evaluating conventional MCI preparation prioritized interagency practice, role alignment, realistic casualties, permission to make mistakes, and structured debriefing [24]. A controlled nursing study found stronger motivation and learning experience with VR but relied mainly on self-report [25]. Together, these studies argue for instructor-led integration and outcome-based debriefing. They do not justify replacing physical contact, equipment handling, team movement, or live interagency coordination.

4 Hybrid Implementation Framework

The framework in Table 2 is the paper's design contribution. It translates the evidence into four phases and preserves the practical insight that VR and physical training solve different instructional problems. Evidence of repeatable triage, decision-making, and performance assessment supports the use of VR for scene scanning, prioritization, communication, guideline rehearsal, and feedback [3, 6, 8, 12, 13, 15, 16]. Findings on usability, technical interruptions, instructor involvement, and debriefing inform the readiness, pilot, and integration phases [19–25]. Live, manikin-based, and instructor-

led comparisons support retaining physical training wherever tactile information, force, dexterity, equipment setup, transport, team movement, or interagency command must be demonstrated [1, 2, 9, 11]. Practice-based security education has likewise been reported to build applied experience and work habits [27].

The framework is modular. Novices begin with stable cases, explicit prompts, immediate feedback, and one decision objective. Prompts are then withdrawn and patient count, ambiguity, distractions, and team dependencies increase. Advanced scenarios may add changing hazards, treatment complications, and instructor-controlled events, but difficulty is changed only after baseline competence is demonstrated. Automated metrics should inform debriefing, not replace expert judgment; speed must always be interpreted with accuracy and safety. The sequence also responds to the evidence gaps identified in this review: gradual exposure addresses usability and symptom concerns, transfer testing checks whether virtual performance carries into physical practice, and repeated follow-up addresses the scarcity of retention data.

Table 2. Four-phase hybrid implementation framework and progression gates.

Phase	Core actions	Progression gate	Required physical link
1. Readiness	Define learners, competencies, baseline, governance, accessibility, data handling, and total cost	Named owner; measurable outcomes; approved risk and data-management plan	Map every VR objective to the corresponding practical assessment
2. Pilot	Build one or two priority scenarios; train instructors; test equipment, debriefing, symptoms, and usability	Technical reliability and tolerability acceptable; no loss of accuracy versus baseline	Validate manual steps on task trainer/manikin
3. Integration	Add graduated modules, scheduled repetition, team roles, and standardized feedback	Competence transfers to blinded physical or live assessment	Periodic hands-on and interagency exercises
4. Scale and improve	Monitor retention, equitable access, cost per learner, incidents, updates, and scenario validity	Sustained outcomes at 3, 6, and 12 months and justified resource use	Regular, measured live exercise and remediation pathway

Note: The progression gates are evidence-informed implementation recommendations, not empirically validated thresholds.

A minimum evaluation set should include triage accuracy, critical-action completion, time interpreted alongside accuracy, communication completeness, protocol deviations, and instructor-rated teamwork. Retention should be rechecked at locally feasible intervals such as three, six, and twelve months. Implementation outcomes should include headset uptime, failed sessions, cybersickness, accessibility accommodations, instructor time, cost per completed learner, and transfer to a physical or live scenario. The progression gates in Table 2 are evidence-informed implementation recommendations rather than empirically validated thresholds; local programs should define and validate their own acceptable values before using them for consequential advancement decisions.

5 Discussion

5.1 Answers to the Research Questions

For RQ1, recent evidence supports VR as a credible modality for emergency and MCI education, but the direction and magnitude of benefit depend on the comparator, outcome, population, and scenario. Controlled comparisons report broadly similar outcomes in some settings and advantages in selected triage or OSCE measures. Evidence concerning retention is limited and mixed: one crossover trial reported higher 30-day knowledge retention, whereas three-month tourniquet performance did not differ significantly from instructor-led training. VR also provides granular assessment of timing, accuracy, information transmission, and error patterns. Stress can be elicited, but its fidelity and educational value remain uncertain. Because the evidence spans paramedic and nursing students, medical trainees, military personnel, and practicing prehospital clinicians, findings should be transferred across groups only with appropriate caution.

For RQ2, successful adoption requires more than purchasing headsets. Scenario validity, interface reliability, instructor competence, debriefing quality, infection control, physical space, cybersecurity, and support capacity determine whether learners can focus on the target task. Accessibility planning should address visual, auditory, vestibular, motor, and neurocognitive needs and provide an equivalent non-headset route when necessary. If eye tracking, voice, motion, or physiological data are collected, institutions need explicit purpose limitation, retention periods, access controls, and rules preventing opaque automated scores from becoming high-stakes judgments. This organizational dimension is consistent with safety-culture models centered on management, employee education, working conditions, behavior, and measurable indicators [26].

For RQ3, the four-phase framework offers a conservative path from need analysis to scaled use. Its design elements are linked to observed evidence: repeatable VR practice addresses access and standardization; instructor preparation and debriefing respond to usability and implementation findings; transfer testing addresses the gap between virtual and physical performance; and repeated follow-up addresses limited retention evidence. Its central safeguard is transfer testing: competence demonstrated in VR must be verified in the physical modality relevant to practice. Frequent virtual rehearsal can make rare decision sequences available throughout the year; periodic measured hands-on and live exercises test haptics, equipment, team movement, and coordination. The proposed progression gates are implementation recommendations, not empirically validated thresholds. This division of labor also makes economic evaluation more meaningful. A local business case should compare total lifecycle costs and achieved learning outcomes, rather than generalize a cost ratio from one scenario.

5.2 Limitations and Research Priorities

This is a focused rapid review, not a comprehensive systematic review. It used one biomedical database, English-language records, and single-reviewer screening. Six included records—Brown et al. [1], Mills et al. [3], de Visser et al. [15], Lopez Lopez et al. [17], Eide et al. [22], and Wang et al. [25]—were assessed from indexed abstracts

and verified publisher metadata rather than full texts. This was not equivalent to full study appraisal: their complete methods, risk of bias, unreported outcomes, and full limitations could not be evaluated to the same extent as those of the 19 full-text publications. Their findings were therefore interpreted cautiously and were not used alone to support strong conclusions. Publication bias, rapidly changing hardware, inconsistent definitions of immersion, and heterogeneous outcome measures limit generalization. The evidence arose from heterogeneous populations, including students, medical trainees, military personnel, and practicing prehospital professionals; results from any one group may not transfer directly to all emergency medical responders. Most studies involved students or simulated performance; none established improved patient outcomes, and few measured retention. The proposed framework and its progression gates have not themselves been prospectively validated.

Future trials should preregister competency outcomes, report adverse effects and attrition, use an active comparator, and test transfer in a blinded physical scenario. Follow-up at three, six, and twelve months would distinguish engagement from retention. Multicenter studies should evaluate team and interagency performance, not only individual triage. Economic studies should report development, hardware, licensing, instructor, maintenance, sanitation, space, downtime, and update costs together with cost per competent learner. These measures would enable implementation decisions based on educational value rather than technological novelty.

6 Conclusion

Immersive VR is compatible with the needs of emergency medical responder and mass-casualty training because it makes rare scenarios repeatable, controllable, and measurable. Current evidence reports broadly similar outcomes to established simulation in several settings and selective gains in triage performance and motivation, while evidence concerning retention remains limited and mixed. It does not support broad claims of superiority, stress reduction, or replacement of live training, and its heterogeneous study populations require cautious generalization to emergency medical responders. The appropriate implementation model is hybrid: use VR frequently for cognitive rehearsal, decision-making, communication, and feedback; retain hands-on and live exercises for tactile skills, equipment, movement, and interagency coordination. A staged rollout with explicit safety, accessibility, governance, transfer, retention, and cost gates can protect educational quality, but the proposed gates are implementation recommendations rather than empirically validated thresholds. The next research priority is not a more immersive demonstration, but a multicenter longitudinal test of whether this hybrid model sustains competence and transfers to physical performance.

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Use of Generative AI. During preparation, the author used OpenAI Codex to support language revision, document formatting, and reference verification. The author critically reviewed the resulting text and remains responsible for the accuracy and integrity of the manuscript.

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