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VIRTUAL REALITY IN RARE CRITICAL EVENT TRAINING: A SYSTEMATIC REVIEW OF EFFICACY IN ENHANCING READINESS AND STRESS MANAGEMENT

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ABSTRACT

Training for Rare Critical Events (RCEs)-high-stakes, low-frequency occurrences across specialized fields such as critical care and emergency services-presents formidable educational challenges. Ethical and safety constraints severely limit the opportunity for real-world exposure, leading to significant performance deterioration and high cognitive load when an RCE occurs. Virtual Reality (VR) technology is emerging as an impactful and scalable training solution capable of delivering high-fidelity experiential learning. This systematic review aims to synthesize current evidence on the efficacy of VR-based training in RCE preparation, specifically examining its dual impact on operational readiness in technical and non-technical skills and the development of effective stress management and cognitive coping mechanisms. The review of studies reveals that VR environments designed with high psychological fidelity, significantly enhance procedural adherence, decision-making speed, and non-technical skills during simulated RCEs. Crucially, the literature demonstrates VR's unique capability to safely implement stress inoculation training. Studies comparing pre- and post-VR training show a measurable reduction in physiological stress markers, such as decreased mean heart rate and improved heart rate variability (HRV), along with lower self-reported anxiety during subsequent high-pressure tests. This suggests superior transfer of training for stress management compared to traditional simulation. The evidence supports VR as a potent, justifiable, and cost-effective tool for RCE preparedness, offering unparalleled opportunity for repeated practice under authentic, high-stress conditions. Future efforts must focus on standardizing VR metrics and conducting robust longitudinal studies to confirm the long-term retention of these critical skills.

KEYWORDS

Virtual Reality, Rare Event Training, Critical Incident, Stress Management, Simulation, Stress Inoculation

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1. Introduction

1.1. The Operational and Cognitive Challenge of Rare Critical Events

Rare Critical Events (RCEs) are defined by their low frequency, high impact, and high complexity. These events often trigger a surge in perceived threat, leading to detrimental effects on cognitive processing, a phenomenon known as "cognitive tunnelling" or "stress-induced motor-skill regression" [1, 2]. The core challenge in preparing personnel is not merely transferring knowledge, but ensuring that knowledge and skills remain accessible, accurate, and executable under extreme psychological pressure.

1.2. Deficiencies in Traditional Training Modalities

Traditional RCE training relies heavily on didactic instruction and, when feasible, high-fidelity physical simulation. However, physical simulation is hampered by high operating costs, limited availability of equipment, and, most significantly, the difficulty in realistically and ethically replicating the acute psychological stress and danger cues inherent to an RCE [3]. Furthermore, the complexity of setting up and resetting scenarios often restricts the necessary deliberate practice required for mastery-based learning, especially for low-frequency events.

1.3. Virtual Reality: Bridging the Training Gap

Virtual Reality (VR) technology-encompassing head-mounted displays (HMDs) and high-fidelity 360-degree environments-offers a paradigm shift in RCE training. VR provides an accessible, repeatable, and highly controllable environment capable of replicating both the technical demands and the psychological fidelity of RCEs [4]. Its key benefits include: (a) Scalability: allowing for wide deployment; (b) Cost-Effectiveness: reducing dependence on physical resources; and (c) Data Objectivity: providing granular metrics on performance, response time, gaze patterns, and physiological responses.

1.4. Rationale and Significance of the Review

While the adoption of VR in various training domains is accelerating, a comprehensive and systematic synthesis focusing specifically on the dual outcomes of RCE preparedness skill efficacy and stress management is critically needed. This review addresses the fragmentation in the literature by systematically evaluating evidence from robust empirical studies. The findings will be crucial for training program developers, policymakers, and researchers seeking to justify and optimize VR implementation for high-risk professions.

1.5. Aims and Objectives

The primary objectives of this systematic review are to:

Quantify Efficacy: Determine the extent to which VR training improves objective measures of technical and non-technical skill performance during simulated RCEs.

Assess Stress Management: Evaluate the impact of VR on reducing psychological and physiological indicators of stress and improving cognitive performance under high-pressure conditions.

Benchmark: Systematically compare the transfer-of-training effectiveness of VR against traditional simulation methods in RCE contexts.

2. Methodology

2.1. Protocol and Registration

This systematic review was rigorously planned and conducted in strict adherence to the guidelines outlined in the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) Statement, utilizing the PRISMA 2020 checklist and flow diagram to ensure comprehensive and transparent reporting [5].

A detailed protocol for this systematic review was drafted prior to the initiation of the literature search. This protocol explicitly defined:

1. The Research Question: Formulated according to the Population, Intervention, Comparison, Outcome, and Study Design (PICOS) framework (as detailed in Section 2.2).
2. Eligibility Criteria: Specific criteria for selecting relevant studies, including inclusion and exclusion filters.
3. Search Strategy: The complete list of databases, controlled vocabulary (MeSH terms), and free-text keywords (as detailed in Section 2.3).
4. Data Extraction Process: The standardized form and the roles of two independent reviewers.
5. Risk of Bias Assessment: The specific quality assessment instruments to be employed (as detailed in Section 2.4).

The availability of this detailed, pre-specified protocol ensures the transparency and reproducibility of the review process. The final report follows the protocol, and any minor deviations necessitated by the retrieved literature will be explicitly reported and justified within the methodology and discussion sections of this paper.

2.2. Eligibility Criteria

The selection criteria were strictly defined using the PICOS framework:

P (Population): Individuals and teams whose roles involve the management of Rare Critical Events (e.g., medical residents, military personnel, astronauts, policemen, firefighters).

I (Intervention): Any VR-based simulation training employing head-mounted displays or fully immersive projection systems designed to replicate RCEs.

C (Comparison): Studies must include a comparison group (e.g., no intervention, traditional classroom training, low-fidelity simulation, or non-VR high-fidelity simulation).

O (Outcomes): Primary outcomes include objective measures of performance (e.g., task completion rates, adherence to protocol, teamwork scores) and measures of stress/cognitive load (e.g., heart rate, HRV, STAI, NASA-TLX).

S (Study Design): Randomized Controlled Trials (RCTs), quasi-experimental designs, and controlled before-and-after studies published in English, in peer-reviewed journals. Review articles, editorials, and case studies without comparative data, published over 5 years ago, were excluded.

2.3. Search Strategy and Data Sources

A comprehensive search was performed on November 2025 across the following electronic databases: PubMed/MEDLINE, Scopus, Web of Science. The search strategy was developed and iteratively refined with a subject expert. The final strategy combined controlled vocabulary and free-text keywords:

(("Virtual Reality" OR VR OR "Immersive Training" OR "Augmented Reality" OR "Extended Reality") OR ("Critical Incident" OR "Crisis Management" OR "High-Risk Training" OR "Emergency Medicine") OR ("Stress Inoculation" OR "Physiological Stress"[tiab] OR "Cognitive Load" OR "Teamwork" OR "Situational

Awareness")). Reference lists of included articles and key review papers were also manually screened to identify additional relevant studies.

2.4. Study Selection and Data Extraction

Full texts of potentially relevant articles were retrieved and assessed for final inclusion. A standardized data extraction form was used to collect: Study characteristics (authors, year, country, study design); Population details (sample size, profession, experience level); VR system specifics (hardware, degree of fidelity, duration of training); Comparison intervention details; Specific outcome measures and key results (including effect sizes and statistical significance). Two independent reviewers [J..B and J.B.S.] assessed the full-text reports for final inclusion.

2.5. Quality Assessment and Data Synthesis

The methodological quality and risk of bias for included studies were assessed. The Cochrane Risk of Bias tool was applied to RCTs, focusing on sequence generation, allocation concealment, blinding, and selective reporting. The Newcastle-Ottawa Scale (NOS) was utilized for assessing non-randomized studies. Data synthesis was performed narratively due to the anticipated heterogeneity in VR platforms, populations, and outcome measures. Results were grouped based on the primary outcomes: (a) Technical and Non-Technical Readiness, and (b) Stress Management and Cognitive Load.

3. Results

3.1. Study Characteristics and Flow

Overall, 18 studies met the inclusion criteria, primarily focusing on high-risk sectors such as healthcare, astronauts, policemen and first response.

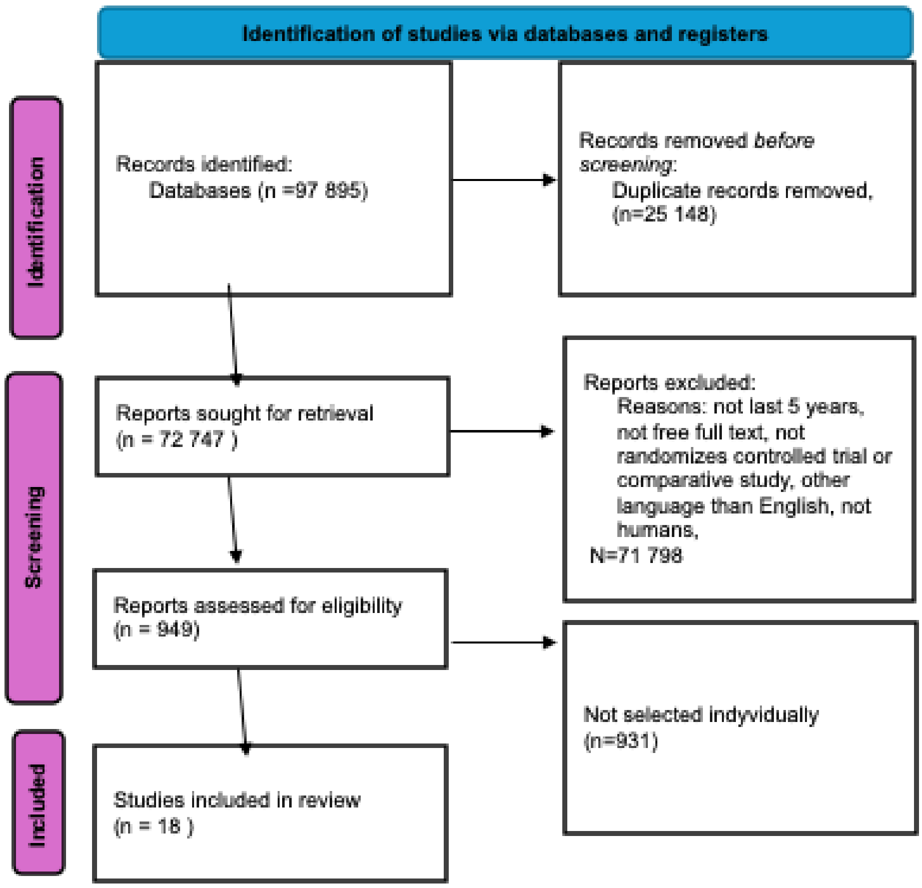

__Fig. 1.__ Prisma 2020 Flow Diagram Illustrating the Selection Process

3.2. VR Efficacy in Enhancing Technical Readiness

Procedural Accuracy and Protocol Adherence: Evidence suggests that VR-trained groups demonstrate significantly higher adherence to critical checklists and protocols compared to control groups [18]

Time-to-Intervention: Several studies [19, 20] documented a reduced time taken to complete the initial critical step (e.g., securing an airway, initiating a shutdown procedure) post-VR training [11,14].

3.3. VR Efficacy in Enhancing Non-Technical Readiness

VR training appears highly effective in improving non-technical skills, which are crucial under high stress. Communication scores (using standardized tools like the Crisis Resource Management [CRM] rating scale) were consistently higher for VR-trained teams [2].

The ability to objectively replay the VR scenario (debriefing) facilitates the targeted identification and correction of leadership and communication failures, a capability often limited in traditional simulation. [10]

3.4. VR Efficacy in Stress Management and Tolerance

Physiological Outcomes: Studies utilizing biometric data show that repeated exposure to RCEs in VR leads to stress inoculation. Following VR training, trainees exhibited a dampened physiological response in a subsequent high-fidelity simulation, characterized by lower peak heart rates and improved HRV, indicating better parasympathetic function and emotional regulation [10, 15, 16, 17].

Psychological Outcomes: Subjective measures corroborated these findings. Trainees reported significantly lower levels of perceived stress (NASA-TLX) and state anxiety (STAI-S) when managing the same RCE post-VR exposure, suggesting a beneficial shift in cognitive appraisal of the threat. [15]

3.5. Comparative Analysis: VR vs. Traditional Simulation

In direct comparisons, VR was often found to be non-inferior to high-fidelity physical simulation for technical skills but superior for stress inoculation, likely due to the ease of scenario repetition and customization of stressor intensity. [12]

Furthermore, in terms of cost-effectiveness and accessibility, VR demonstrated clear logistical advantages for widespread RCE training. [18]

4. Discussion

4.1. Synthesis of Principal Findings

The core finding of this review is the robust evidence supporting the utility of VR training in enhancing both the psychomotor efficiency and cognitive resilience required for managing RCEs. The superiority of VR is most pronounced in its unique capacity to provide safe, repeated, and measurable exposure to high-stress conditions.

4.2. Theoretical Underpinnings of VR Effectiveness

VR's impact can be explained through several psychological theories:

Stress Inoculation Theory (SIT): VR facilitates SIT by introducing stressors in a graded, controlled manner. This allows trainees to develop coping mechanisms (rehearsal, self-talk, emotional regulation) before exposure to a real threat, thereby transforming a potential crisis into a manageable challenge [6].

Cognitive Load Theory (CLT): Well-designed VR simulations can manage extrinsic cognitive load (load imposed by the training design) while maximizing germane cognitive load (load leading to learning). The immersion minimizes external distractions, focusing mental resources on the critical task, which is vital for RCE management where cognitive capacity is a scarce resource. [8]

Context-Dependent Memory: By creating a highly realistic, contextual environment, VR training leverages the principles of context-dependent memory, enhancing the transfer of learned skills from the simulated environment to the real-world operational setting [7, 9].

4.3. Moderators of VR Training Success

The degree of success is critically influenced by:

Fidelity (Psychological over Physical): Studies show that psychological fidelity (the emotional realism) is more important than purely visual fidelity for stress management outcomes. The VR environment must convey the perceived consequences of failure [13].

Debriefing Quality: The effectiveness of VR is maximized when coupled with structured, immediate, video-recorded debriefing that uses the objective performance data captured by the system to address both technical errors and behavioral responses to stress.

Scenario Design: Successful RCE VR modules feature escalating difficulty, introducing new, unexpected variables to test the trainee’s adaptability, moving beyond simple procedural recall.

4.4. Limitations of the Current Literature and Review

The current body of evidence, while compelling, is not without limitations. Heterogeneity across VR hardware, software, and scenario designs complicates direct meta-analytic comparison. A crucial knowledge gap exists regarding long-term retention. While short-term gains are evident, there is insufficient evidence to determine the optimal re-training interval for RCEs using VR. Furthermore, current literature sometimes lacks blinding, introducing potential bias in self-reported outcome measures.

5. Conclusion and Future Directions

This systematic review confirms that Virtual Reality represents a powerful, evidence-based training paradigm for preparing personnel to manage Rare Critical Events effectively. VR training significantly enhances operational readiness across both technical and non-technical domains and provides a unique, safe avenue for stress inoculation, leading to measurable improvements in cognitive and physiological stress management capabilities. The technology successfully addresses the fundamental limitations of traditional training by offering scalable, repeatable, high-fidelity practice under authentic pressure. Implementing VR for RCE training is not merely an optional enhancement but a justified necessity for organizations prioritizing resilience, safety, and peak performance in high-risk environments.

Future Directions for Research

1. Standardization of Metrics: Development and validation of a core set of standardized, objective performance and stress metrics specifically for VR RCE training to allow for robust cross-study comparison.

2. Longitudinal Retention Studies: Conducting large-scale, multi-center trials with follow-up periods exceeding one year to determine the long-term decay rate of VR-acquired skills and the optimal schedule for booster training.

3. Haptic and Multimodal Integration: Investigating the added value of integrating advanced haptic feedback (touch) and olfactory cues (smell) to further boost psychological fidelity and stress response transfer.

4. Cost-Effectiveness Modelling: Detailed economic analyses comparing the initial investment, maintenance, and long-term benefit of VR-based RCE training against traditional high-fidelity simulation.

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