Research Article

Game-based Virtual Reality Technology for HAZMAT Response Training: Enhancing Critical Thinking Attitudes

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Abstract

Game-based virtual reality (VR) technology represents an innovative educational approach, which can effectively engage learners by offering realistic, immersive training environments. This method holds promise in disaster preparedness and emergency response training, because it allows trainees to practice critical skills in interactive, lifelike scenarios with greater engagement and at lower cost than traditional methods. This study investigated the effectiveness of game-based virtual reality for hazardous materials (HAZMAT) emergency response training. 47 undergraduate participants participated in simulated scenarios under time constrains. Assessment methods included multiple-choice tests for knowledge, behavioral sequence scoring for decision-making, and self-reflection questionnaires for critical thinking. Results showed significant improvements in content knowledge (7.34±1.5 to 7.96±1.5, $p<0.05$) and critical thinking (54.51±6.7 to 58.30±3.1 out of 60, $p<0.01$). Participants achieved an average behavioral sequence score of 84.4/100, demonstrating enhanced cognitive processing. Most participants reported that VR-based training was effective for learning and developing critical thinking skills. The findings suggest that VR technology offers a promising, cost-effective alternative to traditional emergency response training methods.

Keywords: Interactive Learning; Virtual Reality in Emergency Training; HAZMAT Response Education; Game-based Learning; Critical Thinking

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บทความวิจัย

เทคโนโลยีเสมือนจริงในรูปแบบเกมสำหรับการฝึกอบรมการตอบโต้อุบัติภัยสารเคมี: การเสริมสร้างทัศนคติเชิงคิดวิเคราะห์

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บทคัดย่อ

เทคโนโลยีความจริงเสมือนแบบเกมเป็นรูปแบบการศึกษาที่มีประสิทธิภาพดึงดูดผู้เรียนด้วยสภาพแวดล้อมที่สมจริง มีศักยภาพในการฝึกการเตรียมความพร้อมสำหรับภัยพิบัติและตอบสนองต่อเหตุฉุกเฉิน ช่วยให้ผู้เรียนฝึกทักษะที่สำคัญในสถานการณ์โต้ตอบเสมือนจริง เพิ่มการมีส่วนร่วม และลดต้นทุนกว่าวิธีการแบบเดิม งานวิจัยนี้ศึกษาประสิทธิภาพของการใช้เทคโนโลยีความจริงเสมือนแบบเกมฝึกทักษะการตอบสนองภัยจากสารเคมี โดยใช้การวิจัยกึ่งทดลองผู้เข้าร่วมเป็นนักศึกษาระดับปริญญาตรี จำนวน 47 คน ใช้อุปกรณ์แสดงผลขนาดเล็กร่วมกับแว่นที่มีหน้าจอติดตั้ง การประเมินความรู้จากการทดสอบแบบเลือกตอบ การเชิงคิดวิเคราะห์ถูกประเมินจากคะแนนลำดับการแสดงพฤติกรรม ประเมินจากกระบวนการตัดสินใจจากสถานการณ์ที่เกิดขึ้นตามสถานการณ์ในเกม ผู้เข้าร่วมถูกจับเวลาตลอดการทดสอบภายในสถานการณ์จำลอง และใช้แบบสอบถามสะท้อนตนเองด้วยมาตราส่วน 5 ระดับ เกี่ยวกับทักษะเชิงคิดวิเคราะห์ ผลการศึกษาแสดงให้เห็นว่าผู้เข้าร่วมมีความรู้เพิ่มขึ้นอย่างมีนัยสำคัญ (จาก 7.34±1.5 เป็น 7.96±1.5, $p<0.05$) และการคิดอย่างมีวิจารณญาณพัฒนาอย่างมีนัยสำคัญ (54.51±6.7 เป็น 58.30±3.1 จากคะแนนเต็ม 60, $p<0.01$) คะแนนเฉลี่ยในการให้คะแนนลำดับพฤติกรรมที่ 84.4/100 แสดงถึงการพัฒนากระบวนการทางความคิด ผู้เข้าร่วมส่วนใหญ่ให้ความเห็นว่าเกมที่ใช้สถานการณ์จำลอง มีประสิทธิภาพในการเรียนรู้และคิดวิเคราะห์ สามารถบูรณาการเข้าในการฝึกอบรมด้านฉุกเฉินในอนาคต

คำสำคัญ: การเรียนรู้เชิงโต้ตอบ; ความเป็นจริงเสมือนในการฝึกอบรมภาวะฉุกเฉิน; การศึกษาการตอบสนองอุบัติภัยจากสารเคมี; การเรียนรู้แบบเกม; ทักษะเชิงคิดวิเคราะห์

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Introduction

Critical thinking is a fundamental component of education, and it involves the active and skillful process of questioning, interpreting, and evaluating information to improve problem-solving and decision-making (The Foundation for Critical Thinking, n.d.). This cognitive approach guides judgments through a thorough examination of facts, careful consideration of outcomes, and incorporation of multiple perspectives (Schafersman, 1991). In emergency response scenarios, particularly hazardous materials incidents, critical thinking becomes vital due to the urgent and unpredictable nature of evolving crises that demand rapid and informed decisions to effectively mitigate potential risks (Leigh, 2016; Albanese & Paturas, 2018).

Emergency response training has evolved to address these complex challenges. Traditional approaches like tabletop simulations (Edzén & Sein, 2016) and functional drills (Agboola et al., 2013) provide essential foundational practices, but cannot fully replicate the dynamic nature of hazardous materials incidents. In response, computer-assisted simulations emerged as a more versatile alternative, enabling the repetition of practice without exposure risks related to complex HAZMAT scenarios.

Virtual reality (VR) technology has revolutionized HAZMAT emergency response training by creating immersive environments that can simulate chemical processes and containment challenges (Sherman & Craig, 2003). These platforms enable trainees to visualize less visible threats and practice decontamination procedures in controlled settings. Research by Tena-Chollet et al. (2017) demonstrates how effectively games in semi-virtual environments can support coordination and decision-making during chemical emergencies, while Sætren et al. (2021) highlights the psychological well-being and realistic context provided by simulator-based training.

Recent integration of game-based learning (GBL) with VR has further enhanced HAZMAT training capabilities. These advanced platforms facilitate practice of critical procedures while providing immediate feedback on decision makers (Checa & Bustillo, 2020; Mao et al., 2021). The ability to record and review response sequences helps trainees to refine their risk assessment strategies (Herrington & Kervin, 2007), whereas Silva et al. (2017) emphasize the importance of evaluating the effectiveness of VR in producing measurable improvements.

The incorporation of critical thinking frameworks into the VR-based HAZMAT training addresses key emergency response requirements. By creating realistic scenarios that challenge assumptions and biases, these platforms foster robust decision-making skills (Raisa et al., 2022). The functionality to practice responses across various chemical incidents, weather conditions, and population densities builds the necessary confidence and leads to the required adaptability (Bailin, 2002; Carlgren, 2013; Kahlke & White,

2013). Learning from expert teams through VR simulations proves vital for integrating critical thinking practices into comprehensive HAZMAT emergency response frameworks.

Research Objective

This research evaluated the effectiveness of VR-based games in developing critical thinking skills during emergency response training, as outlined in the conceptual framework of Figure 1.

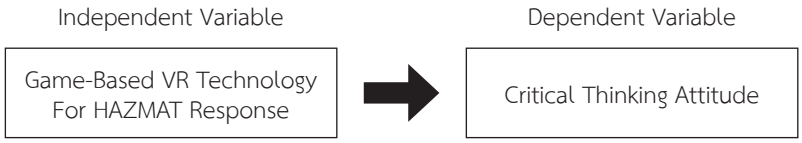


Figure 1. Conceptual Framework

Research Methodology

This study utilized a non-experimental, single-group post-test design to evaluate the effectiveness of an immersive virtual reality (IVR) game for an emergency response training for undergraduate students. It was conducted between April 4th and July 22nd, 2022, at Mae Fah Luang University. The research protocol received full approval from the university's Human Research Ethics Committee (approval number EC22021-18).

Participants

The study involved 47 undergraduate students (25 male, 22 females; mean age 21.3±1.2 years) recruited from the Occupational Health and Safety Program, School of Health Sciences at Mae Fah Luang University, Chiang Rai. All participants were enrolled in the Emergency Preparedness and Response course and had completed prerequisite courses in Basic Chemistry and Hazardous Materials Management. This ensured that all participants possessed the foundational knowledge, which is necessary for emergency response training. The exclusion criteria for the study included students with medical conditions that could affect their ability to use virtual reality (VR), such as epilepsy, severe motion sickness, or vestibular disorders. Students who declined to participate or those who missed the prerequisite theoretical sessions were also excluded.

Research Instrument

The study categorized VR systems into three types: screen-based general, projector-based customized, and head-mounted display (HMD)-based intuitive systems. It utilized the BOBO Z5 VR Glass with a Bluetooth remote controller, employing an HMD approach where the Android smartphones acted as both the monitor and the computer. Learners navigated and interacted with virtual scenarios using the Bluetooth remote,

designed for movement and object interaction. The IVR-based emergency response game incorporated strategies from the Emergency Response Guidebook (U.S. Department of Transportation, 2020) and the National Fire Protection Association (NFPA) Standards (National Fire Protection Association 2008), tailored to scenarios based on past chemical accidents in Chiang Rai Province, Thailand. The content was reviewed by emergency response specialists, who provided feedback on iterative adjustments during the three stages of implementation. (Kobes et al., 2010). The study consisted of three distinct phases:

Pre-Learning Phase

Participants first completed a baseline assessment of their critical thinking skills through a comprehensive questionnaire. They then received structured training on head-mounted display (HMD) operation and safety protocols. Sufficient practice time was allocated to ensure that all participants could comfortably navigate the VR interface and understand all device functionalities.

Learning Phase

During the immersive training session, participants used the HMD and engaged with a simulated emergency scenario. The behavioral response and decision-making pattern of each participant were systematically recorded as they navigated the 360-degree virtual environment. To prevent potential motion sickness and ensure optimal learning conditions, each self-directed session was limited to 360 seconds and conducted in a controlled space. While participants could repeat the scenario multiple times to achieve proficiency, only the data from their initial attempts was included in the analysis.

Post-Learning Phase

Following the VR intervention, participants completed two assessments, a post-test evaluating their emergency response performance, and a follow-up questionnaire measuring the changes in their critical thinking skills. They also provided detailed qualitative feedback about their learning experience with the VR platform.

Data Analysis

The study utilized multiple assessment tools to evaluate various dimensions of learning and performance.

Knowledge Assessment (10 items)

The assessment of knowledge in this study utilized a combination of multiple-choice questions and scenario-based questions. Six items were designed to test factual recall, while four items evaluated the conceptual understanding in an emergency response context. The content was rigorously validated by three experts in emergency response field, so that it achieved a high content validity index (OCI=0.97). The scoring was straightforward, for each correct answer getting 1 point. This resulted in a total

possible score of 10 points. The categorization of knowledge levels based on the scoring is detailed in Table 1.

Table 1. Classification of participation knowledge levels based on percentage scores

Scoring Knowledge Score			Score out of 10
Level of Knowledge	**Sub-variable**	**Percentage**	
Inadequate	Very Poor	<20	0.0–2.0
	Poor	20-40	2.0–4.0
Moderate	Average	41-60	4.1–6.0
	Good	61-80	6.1–8.0
Adequate	Very Good	81-90	8.1–9.0
	Excellent	>91	9.1–10

Critical Thinking Skills Assessment

The study employed a pre- and post-self-reflection questionnaire consisting of 12 items to evaluate the critical thinking and practical skills of the participants. Responses were measured using a five-point Likert scale, ranging from 1 (Strongly Disagree) to 5 (Strongly Agree), with a total score of 12 and 60 points, repectively. The questionnaire assessed four key areas: problem identification and analysis, decision-making under pressure, risk assessment capabilities, and the application of emergency protocols. This tool aimed to capture changes in the self-perceived competencies of the participants before and after training intervention.

Behavioral Sequence Assessment

The actions of all participants were observed across four sequential VR scenarios, and their performance was evaluated using standardized rubrics tailored to each scene. The assessment focused on key competencies, which are critical to emergency responses, including the effective communication of chemical information, the establishment of perimeter security, the appropriate selection of containment equipment, and the proper operation of fire extinguishers. These competencies were chosen to reflect the essential skills required for effectively managing hazardous material incidents.

Critical thinking skills were evaluated by analyzing learners' decision-making processes, offering insights into individual behaviors when responding to questions and sequencing key events in emergency responses within the IVR-based game scenario. The behavioral sequence score was derived from a sequence diagram, which was illustrating the critical events across all emergency response stages.

Scene 1: Emergency communication: Learners demonstrated the ability to identify and accurately convey critical chemical information, including hazard pictograms, UN identification numbers, and chemical status assessments, to emergency responders.

Scene 2: Safety zone establishment: Learners showed their competency in defining and securing an appropriate safety perimeter to protect bystanders and prevent unauthorized access to hazardous areas.

Scene 3: Chemical containment: Learners demonstrated proper selection and deployment of containment equipment to effectively manage chemical spills, while adhering the relevant safety protocols.

Scene 4: Fire response: Learners showed correct use of fire extinguishers, including the appropriate selections, approaches, and application methods for fire suppression.

Statistical Analysis

Descriptive statistics were computed for each variable and general characteristics der calculated, like frequency, percentage, mean, and standard deviation. A paired samples T-test was conducted to assess the statistical significance of correlations observed.

Research Results

Participant Demographics

From the 47 undergraduate students, the majority were female (80.85%, n=38) and third-year students (95.47%, n=45), with an average age of 21.13±0.74 years (Table 2). This homogeneous sample provided a consistent baseline for evaluating the impact of VR on the critical thinking development.

Table 2. General characteristic of participants (N=47)

Characteristic	N	%
Gender		
Male	9	19.15
Female	38	80.85
Age		
20 years and younger	4	8.51
21-22 years	41	87.23
23 years and older	2	4.26
Year of study		
Second-year students	2	4.26
Third-year students	45	95.47

Knowledge Acquisition and Critical Thinking Development

The study assessed the effectiveness of an IVR-based game scenario for emergency response by using pre- and post-test designs. Students took a knowledge test both before and after participating in the IVR-based game. Table 3 displays the scores out of

10 points. The related T-test values for dependent samples indicate a statistically significant P-value of 0.004 ($p<0.05$).

Table 3. Knowledge (N=47)

Knowledge Test	$\bar{X}$	S.D.	t	Sig.(two-tailed)
Pre-test	7.34	1.49	-3.074	0.004
Post-test	7.96	1.50		

The comparison of pre- (7.34±1.49) and post-test (7.96±1.50) scores showed a statistically significant improvement ($p=0.004$), underscoring the effectiveness of the VR intervention. This improvement was closely linked to specific VR elements, which were designed to improve the critical thinking skills. One key factor was the real-time decision-making, where a first-person perspective required the participants to make independent choices under time constrains. A high behavioral sequence score (80-100 points) was achieved by 74.47% of the participants, reflecting the successful development of systematic thinking skills in crisis scenarios. The average completion time was 263.8 seconds (out of 360), which suggests that participants made deliberate and thoughtful decisions rather than rushed responses.

The sequential learning progression of the VR scenario supported the critical thinking development through four distinct stages. During the initial assessment phase, participants scored 80-100 points in information gathering and risk assessment. Strategic planning, characterized by a scenario analysis, was demonstrated by mid-range performers (60-79 points, 14.89%). Lower performers (0-59 points, 10.64%) primarily faced challenges in applying theoretical knowledge to practical situations.

Several engagement factors contributed to the cultivation of critical thinking. These included interactive chemical identification tasks that required the participants to synthesize prior knowledge, dynamic emergency scenarios, which demanded a rapid problem assessment, and real-time feedback, which needed self-reflection and adjustment. The first-person perspective played a significant role in enhancing the personal responsibility for decision-making and supported the development of critical thinking skills.

Critical Thinking Growth Patterns

Critical thinking in the IVR-based game scenario was designed to assess the decision-making skills of the participants during emergency responses. The scenario incorporates prompts and cues to assist participants in navigating through the necessary procedures for managing the emergencies. The cognitive process, which was shown by the students' decision-making, was quantified through a behavioral sequence score ranging from 0 to 100 points. This score showed three distinct patterns of critical thinking

development (Table 4).

Table 4. Process of thinking (N=47)

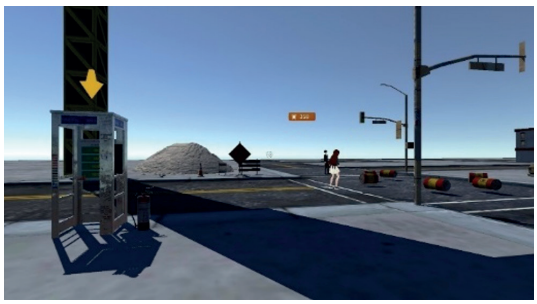
Behavioral sequence score	N	%
0-59	5	10.64
60-79	7	14.89
80-100	35	74.47
Total	**47**	**100**

Advanced performers (74.47%) demonstrated integrated thinking and exhibited confidence in their decision-making, so that they successfully navigated complex scenarios with minimal difficulty. Developing participants (14.89%) showed emerging critical analysis skills, indicating a progress, but they require additional support when facing more complex decisions. Participants at the basic level (10.64%) struggled to bridge the theoretical knowledge with practical applications, indicating the need for further guidance and targeted interventions to strengthen their understanding and application of emergency response protocols.

Participants performed well on the assessment, with a mean score of 84.4 points (maximum 100). The mean task completion time was 263.8 seconds, which was well within the 360-second time limit. The IVR scenario presented a first-person, single-user experience where participants progressed through a sequence of events (see Figure 2A-G). Critical thinking abilities were assessed using a 12-item self-concept questionnaire. The analysis revealed significant differences ($p<.001$; see Table 5).

Table 5. Critical thinking (N=47)

Critical thinking Score	$\bar{X}$	S.D.	t	Sig.
Pre-Immersive Virtual Reality	54.51	6.71	-3.924	0.000
Post-Immersive Virtual Reality	58.30	3.13		



A - Once the emergency scenario is loaded, the participant is standing on the road.



B - The vehicle with the barrel of hazardous chemicals is unexpectedly in an accident, and the chemical containers leak.



C - Looking around the accident scene, and going to a phone booth, and providing complete information to the relevant authorities.



D - Setting a perimeter to prevent any unauthorized person from entering the accident area.



E - Finding surrounding equipment to control the chemical spillage.



F - Sparks and a fire occurred close to the accident area.



G - Taking a fire extinguisher and using it in a correct sequence of commands to extinguish the virtual fire.

Figure 2. Storyline of the immersive virtual reality (IVR)-based game scenario

Discussion

The implementation of IVR-based games in emergency response training demonstrated significant improvements in both knowledge acquisition and critical thinking development. As predicted by Skryabina et al. (2017), the VR-based approach proved to be more effective than traditional training methods, with knowledge scores increasing from 7.34±1.5 to 7.96±1.5 ($p<0.05$), which is supporting the findings by

Chang et al. (2022) on VR's superiority over tabletop drills.

Critical Thinking Development through VR Interaction

The behavioral sequence analysis revealed specific actions that indicated a critical thinking development, which included the systematic analysis of hazard placards and UN numbers during the identification of chemicals, the appropriate risk zone assessment (74.49%), the successfully established perimeter based on chemical properties, the improved resource management in selecting containment equipment, and the enhanced emergency communication for relaying critical information. These outcomes align with Merchant et al.'s (2014) findings on VR's ability to deliver superior learning outcomes in higher education settings.

Technical and Implementation Challenges

While this work is supporting conclusions by Adami et al. (2021) about the effectiveness of VR in procedural knowledge delivery, several challenges remain. Hardware limitations, including mobile HMD resolution, were affecting the hazard placard readability. Bluetooth controller latencies were affecting the response time, and there were limitations in the view field of complex scenarios. User adaptation challenges included the initial disorientation in the 360-degree environment. Participant experienced different levels of comfort with the technology and with the physical space requirement for safe movements. The assessment involved difficulties in standardizing the performance metrics, in simultaneously observing multiple actions, and in refining critical thinking evaluation tools.

Implementation Guidelines for Educational Settings

Based on this experience and supporting Jung and Park's (2022) emphasis on active participation, several recommendations were developed. For the technical setup, institutions need to ensure minimum specifications of the mobile device, to allocate dedicated spaces, and to maintain an adequate support staff ratio. The curriculum integration needs to address the prerequisite knowledge, the optimal session durations, and the robust assessment integration strategies. Resource planning considerations need to include equipment costs, maintenance, technical support requirements, and software update protocols.

Future Research Directions

Adding to Checa and Bustillo's (2020) and Mao et al.'s (2021) work on educational impact, future research need to explore comparisons of mobile versus tethered VR systems, enhancements in haptic feedback, and multi-user scenario development. Advancements in the assessment methodologies is recommended, including the standardization of VR-based critical thinking metrics, the integration of automated performance tracking systems, and longitudinal studies on skill retention. The adaptation

of IVR systems across educational levels, the integration with existing emergency response protocols, and the development of progressive difficulty scenarios need be further investigated.

This research supports the work of Seprum et al. (2021) on emergency response preparation while addressing concerns about the outcome uncertainties through measurable improvements in both knowledge and critical thinking scores (54.51±6.71 to 58.30±3.13). As Kang et al. (2020) suggested, the IVR experience effectively stimulated student interest and motivation, leading to enhanced learning outcomes. These findings demonstrate that IVR-based emergency response training can effectively bridge the gap between theoretical knowledge and practical application while addressing the technological and educational challenges involved in the implementation.

Conclusion

This study demonstrates that IVR-based emergency response training effectively enhances both technical knowledge and critical thinking skills. The documented improvements in behavioral sequence scores (74.49% Achieving Mastery) suggest that VR technology can successfully bridge the gap between theoretical understanding and practical applications. Existing implementation challenges can be effectively managed through proper planning and resource allocation. The results provide a foundation for expanding VR applications in emergency response education, with a clear pathway for future development and research.

Authors Contribution and Conflict of Interest Declaration

Conceptualization/contents and storyline was done by Prapamon S. and Anchalee K., Methodology and visualization was design by Prapamon S. & Pongpon S., The project administration was Prapamon S., Resources & Software was prepared by Pongpon S., Data Analysis, Validation, Writing & Review were completed by Prapamon S. All authors declare no conflicts of interest.

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