

Evaluating the Effectiveness of Virtual Reality-Based Fire Safety Training Using Performance Metrics and User Behavior Analysis

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Abstract—Fire safety training is essential for improving emergency response; however, conventional methods often lack interactivity and fail to provide measurable performance data. Existing Virtual Reality (VR)-based training systems enhance immersion but primarily rely on subjective evaluation, limiting quantitative assessment of effectiveness. To address this limitation, a VR-based fire safety training system integrated with performance metrics and user behavior analysis was developed and evaluated. An experimental study involving 47 participants was conducted using a pre-test and post-test design. Learning outcomes, behavioral data, and user feedback were analyzed. Results indicate a significant improvement, with median scores increasing from 4 to 8 and 70.21% of participants showing improvement. The Wilcoxon signed-rank test confirmed statistical significance ($p = 0.00016$) with a moderate to large effect size ($r = 0.525$). Behavioral metrics further demonstrated measurable user performance, supporting the effectiveness of VR-based fire safety training.

Index Terms—Virtual Reality, Adaptive simulation, disaster simulation, Fire Safety Training, Immersive Learning

I. INTRODUCTION

Fire emergencies pose a significant threat to human life and infrastructure, requiring rapid and informed responses to minimize damage and casualties [1], [2]. Effective fire safety training is therefore essential; however, conventional methods such as lectures and fire drills often fail to provide realistic, hands-on experiences [3], [4]. These approaches typically lack interactivity and do not capture detailed performance data, limiting the ability to evaluate user readiness and behavioral responses. Virtual Reality (VR) has emerged as a promising solution by enabling immersive and controlled training environments [5], [6]. VR allows users to safely experience fire scenarios while supporting repeated practice and experiential learning. Prior studies show that VR improves engagement, decision-making, and situational awareness in emergency contexts [7]–[10]. It has also been applied in fire evacuation modeling and safety training, demonstrating strong practical potential [11]–[15]. Despite these advantages, many VR-based training systems focus primarily on simulation realism or user experience rather than comprehensive evaluation of training effectiveness [16]. Most studies rely on subjective methods

such as questionnaires, which do not provide objective evidence of performance improvement [7], [17]. Although some systems collect interaction data, such as task completion time, these data are rarely systematically analyzed [8], [14]. Consequently, there is a lack of standardized, data-driven evaluation frameworks that incorporate objective metrics such as response time, accuracy, and task efficiency [18]. The relationship between user behavior and learning outcomes also remains insufficiently explored [19].

To address these gaps, this study proposes a data-driven VR-based fire safety training system that integrates immersive simulation with automated event logging. The system captures detailed user interaction data, including response time and task completion, alongside pre-test and post-test evaluations and user feedback [3], [4]. The main contribution of this work is the integration of performance metrics and behavioral analysis to enable objective evaluation of training effectiveness. The results demonstrate that VR-based training can significantly improve user knowledge and response performance while providing measurable evidence of learning outcomes.

II. LITERATURE REVIEW

Virtual Reality (VR) has been increasingly adopted as a training tool in safety-critical domains due to its ability to simulate hazardous environments in a controlled and immersive manner [5], [6]. Prior research has demonstrated that VR-based systems provide a safe platform for users to experience emergency situations, enabling repeated practice and experiential learning without real-world risks [7], [8]. Early implementations of VR in fire safety training focused primarily on simulation and visualization, where virtual environments were used to replicate fire scenarios and evacuation processes [3], [4], [13]. These systems emphasized realism and interaction but provided limited mechanisms for evaluating user performance. A significant body of research has explored fire evacuation behavior using VR-based simulation models. For instance, crowd evacuation dynamics have been studied using improved social force models integrated with virtual environments, enabling the analysis of movement patterns and congestion during emergencies [11]. Similarly, pre-evacuation

behavior has been investigated to understand user decision-making processes before initiating evacuation [9]. Studies on wayfinding strategies have further highlighted the influence of environmental factors, such as signage and spatial familiarity, on evacuation efficiency [10]. In addition, the placement of safety signage and its impact on user behavior has been analyzed using physiological data, providing insights into user responses under stress conditions [12]. Additional VR-based evacuation training systems have also explored collaborative and immersive training environments to enhance realism and user engagement [14], [15]. While these studies contribute to understanding human behavior in emergency scenarios, their primary focus remains on behavioral modeling and environmental design rather than on training effectiveness. Most of these approaches aim to simulate realistic scenarios or predict evacuation outcomes, but they do not incorporate structured evaluation frameworks to assess user learning or performance improvement [2]. In parallel, several studies have investigated the effectiveness of VR as a training tool. Systematic reviews have indicated that VR enhances user engagement, motivation, and knowledge acquisition across various training contexts [7], [8]. Meta-analytical findings further suggest that immersive environments can improve learning outcomes compared to traditional methods, particularly in skill-based training scenarios [17]. Additionally, the role of specific VR features, such as immersion, interaction, and feedback, has been examined to determine their influence on different types of learning outcomes [18]. These studies highlight the potential of VR to support both cognitive and procedural learning. Furthermore, recent immersive training systems have incorporated expert feedback and interactive guidance to enhance training effectiveness [16]. Despite these advancements, the evaluation of VR-based training systems remains predominantly subjective. Many studies rely on questionnaires, Likert-scale responses, and user feedback to assess usability, engagement, and perceived learning outcomes. While such methods provide valuable insights into user experience, they do not offer objective or quantifiable measures of performance. Furthermore, although some systems capture user interaction data, such as movement trajectories or task completion time, these data are often underutilized and not systematically analyzed to evaluate training effectiveness [8], [14]. Another limitation observed in existing literature is the lack of integration between behavioral data and performance metrics. While behavioral studies focus on how users act in simulated environments, and training studies focus on learning outcomes, few approaches combine these aspects to provide a comprehensive evaluation framework. This disconnect limits the ability to establish a direct relationship between user behavior, task performance, and learning improvement [19]. Moreover, existing VR-based fire safety training systems often lack standardized methodologies for assessing effectiveness. There is no widely accepted framework that integrates multiple data sources, such as pre-test and post-test evaluations, system-generated performance data, and user feedback, into a unified evaluation model. As a result, the effectiveness of VR training

is often inferred rather than empirically validated [1].

III. METHODOLOGY

This study adopts an experimental, data-driven approach to design, implement, and evaluate a Virtual Reality (VR)-based fire safety training system. The methodology integrates system development, user interaction, data collection, and statistical analysis to assess the effectiveness of the proposed training framework. The overall process consists of system architecture design, scenario development, participant-based experimentation, and quantitative evaluation using performance metrics and behavioral data.

A. System Architecture

The proposed VR-based fire safety training system was developed to simulate realistic emergency scenarios while capturing detailed user interaction data. The system architecture consists of four primary components: (1) VR simulation environment, (2) user interaction module, (3) data logging module, and (4) data analysis module. The VR simulation environment was developed using Unity, where realistic fire emergency scenarios were created, including fire ignition, smoke propagation, alarm systems, and evacuation routes. Users interact with the environment using VR hardware, enabling immersive navigation and task execution. The user interaction module manages all user actions within the environment, including movement, object interaction (e.g., activating alarms, using fire extinguishers), and decision-making processes during the simulation. The data logging module records real-time user behavior and system events. Key performance indicators such as response time, task completion time, and action sequences are captured and stored in CSV format for further analysis. The data analysis module processes the collected data to evaluate user performance and training effectiveness using statistical methods.

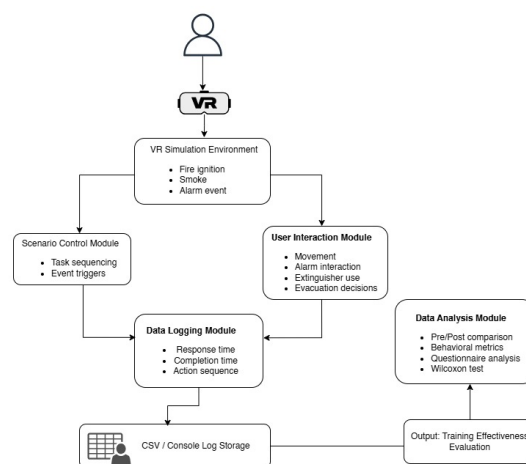


Fig. 1. System Architecture of the VR-Based Fire Safety Training System

A structured fire emergency scenario was designed to guide users through a sequence of critical safety tasks. The scenario begins with the detection of a fire event, followed by a series of required actions, including identifying the hazard, activating the fire alarm, attempting fire suppression using an extinguisher, and safely evacuating the environment. The task flow was designed to reflect real-world emergency procedures and to ensure consistency across participants. Visual cues, such as directional indicators and highlighted objects, were incorporated to guide users without explicitly instructing them, thereby allowing natural decision-making behavior. The system tracks each step performed by the user, including the correctness and sequence of actions, enabling detailed behavioral analysis.

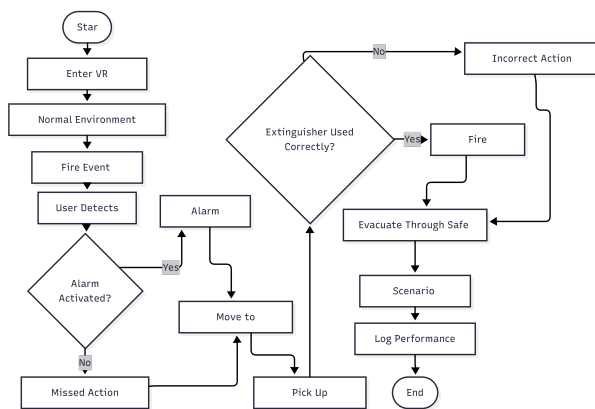


Fig. 2. VR Scenario Logic Flow of the Proposed Fire Safety Training System

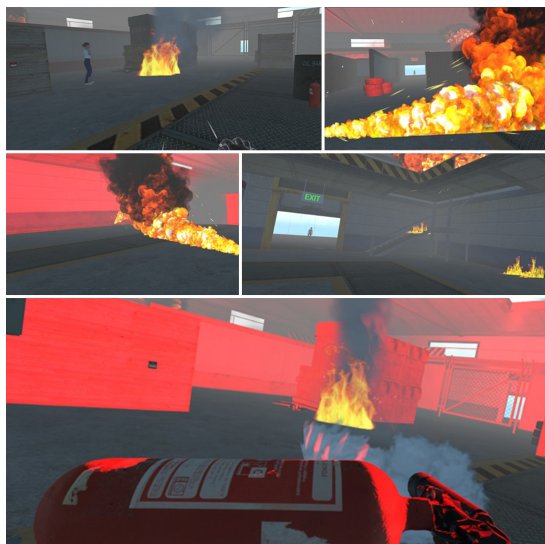


Fig. 3. Screenshots of VR Environment (Fire Scene, Alarm, Evacuation Path)

B. Experimental Design

An experimental quantitative study was conducted to evaluate the effectiveness of the VR-based training system. A total of 47 participants were involved in the study. Participants were recruited from a general student population with varying levels of prior exposure to VR technology. Prior familiarity with VR was not used as an exclusion criterion; therefore, the sample included both users with previous VR experience and users with limited or no VR experience. The experimental procedure followed a pre-test and post-test design to measure learning improvement. Initially, participants completed a pre-test questionnaire designed to assess their baseline knowledge of fire safety procedures. Following this, participants engaged with the VR training system, where they performed the simulated emergency tasks. After completing the VR session, participants were required to complete a post-test questionnaire identical in structure to the pre-test. The pre-test, VR training session, and post-test were conducted on the same day. The post-test was administered immediately after completion of the VR training session to measure short-term learning improvement. Additionally, participants completed a VR system assessment questionnaire to evaluate usability, engagement, and perceived effectiveness of the system. This structured approach enabled the comparison of knowledge levels before and after training, as well as the assessment of user experience.

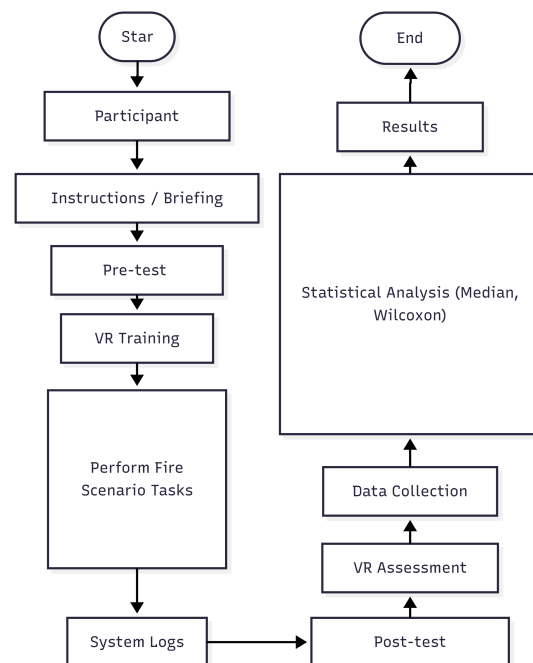


Fig. 4. Experimental Procedure Flow

C. Data Collection and Performance Metrics

Data collection was performed through multiple sources to ensure a comprehensive evaluation. Three primary types of data were collected: **Pre-test and Post-test Scores:** These scores represent participants' knowledge levels before and after the VR training. The difference between these scores was used to evaluate learning improvement. **System-Generated Behavioral Data:** The VR system automatically recorded user interaction data, including:

- Alarm response time (time taken to react to the fire event)
- Task completion time (total time taken to complete the scenario)
- Action sequences and decision paths

These data provide objective insights into user performance during the simulation.

User Assessment Data: A structured questionnaire was used to collect user feedback regarding system usability, immersion, and learning effectiveness. All data were exported and stored in structured CSV files, enabling further statistical analysis.

D. Data Analysis Methods

Due to the nature of the collected data and the sample size, non-parametric statistical methods were employed. The median and interquartile range (IQR) were used to summarize the central tendency and variability of the data. To evaluate the significance of learning improvement, the Wilcoxon Signed-Rank Test was applied to compare pre-test and post-test scores. This test was selected as it does not assume normal distribution and is suitable for paired sample comparisons. The effect size (r) was also calculated to determine the magnitude of the observed changes. Additionally, improvement percentage analysis was conducted to quantify the proportion of participants who demonstrated performance improvement after training. Behavioral performance metrics, such as response time and task completion time, were analyzed using median values to provide a robust representation of user performance.

All participants voluntarily participated in the study, and the data collected were anonymized to ensure privacy and confidentiality. The experimental procedure was conducted in a controlled environment to ensure participant safety during VR interaction.

The proposed methodology integrates immersive VR simulation with a structured experimental design and quantitative data analysis. By combining system-generated behavioral data with pre-test and post-test evaluation, the study enables a comprehensive and objective assessment of training effectiveness. This approach addresses the limitations identified in existing literature by introducing a data-driven framework for evaluating VR-based fire safety training systems.

IV. RESULTS AND DISCUSSION

The effectiveness of the proposed Virtual Reality (VR)-based fire safety training system was evaluated using a combination of learning outcome assessment, behavioral performance metrics, and user experience analysis. The results ob-

tained from the experimental study demonstrate the capability of the system to improve knowledge acquisition and support measurable performance evaluation.

The evaluation was conducted across three dimensions: knowledge improvement, behavioral performance, and user experience. Knowledge improvement was assessed using pre-test and post-test scores, behavioral performance was evaluated using system-generated logs, and user experience was measured through the VR assessment questionnaire.

A. Learning Outcome Improvement

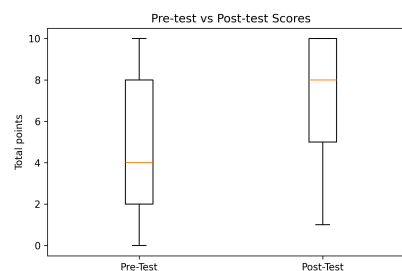


Fig. 5. Comparison of pre-test and post-test scores showing improvement in participant knowledge after VR training.

The comparison between pre-test and post-test scores indicates a significant improvement in participant knowledge after the VR training session. As shown in Fig. 5, the median score increased from 4 in the pre-test to 8 in the post-test, with a median improvement of 3 points. Furthermore, 70.21% of participants exhibited an increase in their scores, indicating a consistent positive learning trend across the sample.

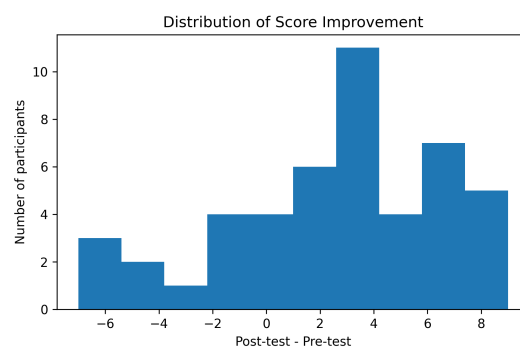


Fig. 6. Distribution of score improvement (post-test minus pre-test) among participants.

To assess the statistical significance of the observed improvement, the Wilcoxon signed-rank test was employed due to the non-parametric nature of the data. The results revealed a statistically significant difference between pre-test and post-test scores ($p = 0.00016$), confirming that the observed improvement is unlikely to be due to chance. Additionally, the

effect size ($r = 0.525$) indicates a moderate-to-large practical impact, suggesting that the VR-based training system has a meaningful effect on learning outcomes. The distribution of score improvement, illustrated in Fig. 6, further supports these findings. While the majority of participants demonstrated positive improvement, a small number of cases with negative or no improvement were observed, which may be attributed to individual differences in learning ability or familiarity with fire safety procedures.

B. Behavioral Performance Metrics

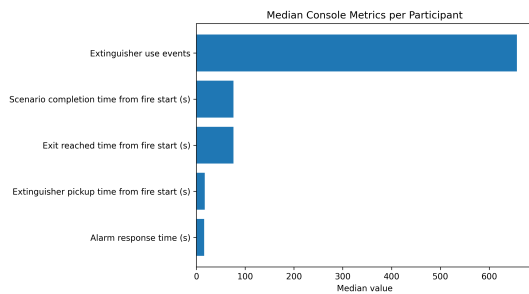


Fig. 7. Median behavioral performance metrics recorded during the VR training session.

In addition to knowledge-based evaluation, behavioral performance metrics were extracted from system-generated logs to provide objective insights into user actions during the VR training session. As shown in Fig. 7, the median alarm response time was recorded as 16.10 seconds, while the median scenario completion time was approximately 76.08 seconds. These results indicate that participants were able to recognize the fire scenario and respond within a reasonable time frame. The relatively short alarm response time suggests effective situational awareness, while the completion time reflects the ability to perform sequential tasks such as locating the extinguisher, attempting fire suppression, and evacuating the environment. Unlike traditional training methods, which rely primarily on observational or self-reported data, the proposed system enables precise measurement of user behavior through automated logging. This allows for a more accurate assessment of performance and provides valuable insights into user decision-making processes during emergency scenarios.

User feedback was collected a structured questionnaire to evaluate the usability and perceived effectiveness of the VR system. The median total score for the assessment was 40, indicating a generally positive user experience. Participants reported that the system was easy to use, realistic, and helpful in understanding fire emergency procedures.

As illustrated in Fig. 8, high median ratings were observed across all assessment items, including system usability, realism of the environment, clarity of instructions, and confidence in using a fire extinguisher. These findings suggest that the immersive nature of the VR environment contributed to enhanced engagement and learning effectiveness.

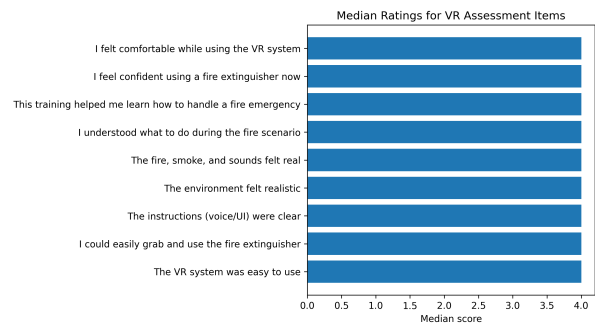


Fig. 8. Median ratings of VR system assessment items reflecting user experience and perceived effectiveness.

TABLE I
SAMPLE OF COLLECTED PARTICIPANT DATA

ID	Pre	Post	Gain	Alarm	Time
P021	2	7	5	74.54	204.99
P022	4	3	-1	89.31	145.33
P023	2	5	3	72.13	139.33
P024	3	5	2	66.84	184.60
P025	2	4	2	55.59	118.19
P026	1	6	5	99.84	169.73
P027	1	8	7	70.32	126.27
P028	8	10	2	69.28	153.17
P029	2	10	8	64.04	100.07

Table I presents a sample of the collected dataset, illustrating both knowledge improvement and behavioral performance metrics recorded during the VR training session. The table highlights the integration of pre-test and post-test scores with system-generated performance data, demonstrating the capability of the proposed system to support comprehensive data-driven evaluation. The results collectively demonstrate that the proposed VR-based fire safety training system is effective in improving both knowledge and behavioral performance. The statistically significant increase in post-test scores confirms the system's ability to enhance learning outcomes, while the behavioral metrics provide objective evidence of user performance during training. The integration of real-time data logging represents a key advantage of the proposed approach, as it enables comprehensive and data-driven evaluation. This addresses a major limitation identified in existing VR-based training systems, which often rely on subjective assessment methods. By combining quantitative performance metrics with traditional evaluation techniques, the proposed framework provides a more robust and reliable assessment of training effectiveness. Furthermore, the positive user feedback indicates that the system is both usable and engaging, which is essential for effective training. The ability to simulate realistic fire scenarios in a safe and controlled environment allows users to practice critical skills without risk, thereby improving preparedness for real-world emergencies. Overall, the findings support the use of VR technology as a powerful tool for fire safety training and highlight the importance of integrating

behavioral data analysis into training evaluation frameworks.

V. CONCLUSION

This study presented a Virtual Reality (VR)-based fire safety training system integrated with performance metrics and user behavior analysis to support a data-driven evaluation framework. The results demonstrated that the system effectively improves user knowledge and emergency response behavior, as evidenced by the significant increase in post-test scores confirmed through the Wilcoxon signed-rank test. Additionally, behavioral metrics such as alarm response time and scenario completion time provided objective insights into user performance during simulation. The integration of automated data logging with immersive VR training represents a key contribution, enabling comprehensive and measurable evaluation beyond traditional methods. However, the study has limitations, including a relatively small sample size and simplified fire scenarios, which may affect generalizability. Future work should involve larger participant groups, more complex scenarios, and advanced analytics such as machine learning and physiological data integration to further enhance evaluation. Overall, the findings highlight VR's potential as an effective tool for fire safety training.

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