DOI: 10.37943/23LTJV6054

Bekzat Ussenov
Bachelor of Science, Department of Software Engineering
220481@astanait.edu.kz, orcid.org/0009-0004-5250-2667
Astana IT University, Kazakhstan

Arnur Temen
Bachelor of Science, Department of Software Engineering
221119@astanait.edu.kz, orcid.org/0009-0002-4925-2615
Astana IT University, Kazakhstan

Zhalgas Srymbetov
Bachelor of Science, Department of Software Engineering
220975@astanait.edu.kz, orcid.org/0009-0008-8998-4099
Astana IT University, Kazakhstan

Azamat Yeshmukhametov
PhD, Instructor, Department of Robotics Engineering,
Institute of Smart Systems and Artificial Intelligence,
azamat.yeshmukhametov@nu.edu.kz, orcid.org/0000-0002-6258-8183
Nazarbayev University, Kazakhstan

Tolegen Akhmetov
PhD, Assistant Professor, Department of Computer Engineering
tolegen.akhmetov@astanait.edu.kz, orcid.org/0000-0002-1712-1269
Astana IT University, Kazakhstan

DEVELOPMENT OF A VIRTUAL REALITY-BASED FIRE SAFETY TRAINING SYSTEM FOR APARTMENT RESIDENTS

Abstract: Fire safety training is crucial for preventing injuries and property damage during emergencies. Traditional training methods, such as physical drills and lectures, suffer from low engagement, high costs, and limited realism. Virtual reality technology offers an innovative approach to improve fire safety education by providing an immersive and interactive training environment. This paper presents the development of a virtual reality-based fire safety training system for apartment residents, designed for a head-mounted display. The system incorporates realistic fire simulations and mechanics for interactive fire extinguishing. Our study explores both qualitative and quantitative measurements of a virtual reality (VR) training model, comparing it with alternative video-based training for fire safety. The experiment involved 20 participants who underwent training using either our VR system or video instructions, divided into two groups. After the VR training, participants completed a presence questionnaire and a knowledge test. Objective metrics included overall escape time and completion rate. Subjective data were collected through semi-structured interviews conducted after the experiments. Results indicate a significant difference in presence scores and higher knowledge scores for the VR group (VR: M = 10.9, SD = 2.37; Video: M = 7.3, SD = 1.33). These findings suggest that immersive VR training enhances procedural learning and situational awareness more effectively than passive video instruction. The study contributes to the field of VR in safety education by offering empirical evidence of its advantages and highlighting gaps in user engagement and realism in conventional methods. Limitations include the small sample size

Received: 23.05.2025 Accepted: 24.06.2025 Published: 30.09.2025

and short-term retention measurement. Future work will explore larger-scale evaluations and the integration of AR for blended learning experiences.

Keywords: fire safety training, virtual reality, immersive learning, fire simulation, interactive training, head-mounted display, emergency preparedness, risk-free training.

Introduction

Fire emergencies remain a critical threat to human life and property, highlighting the importance of effective and practical fire safety training. Traditional methods, such as theoretical lectures, printed manuals, and physical drills, often suffer from limitations including low engagement, high costs, and logistical challenges. Furthermore, these methods typically fail to replicate realistic emergency scenarios, limiting the ability of trainees to develop rapid decision-making skills under pressure [1]. To address these limitations, Virtual Reality (VR) leverages recent advancements in immersive technology to provide an alternative platform for fire safety training, offering the potential for higher realism, interactivity, and scalability.

VR is a computer-generated simulation that allows users to interact with immersive three-dimensional environments in real-time [2]. It creates a sense of presence by combining visual, auditory, and sometimes haptic feedback. This technology has expanded beyond entertainment into fields like education, healthcare, and industrial training, demonstrating its versatility in simulating complex scenarios, improving engagement, and fostering skill development in safe and controlled environments [3].

A growing number of studies have shown that virtual reality (VR) training can be more effective than traditional approaches such as video lessons or physical drills, particularly when it comes to knowledge retention, engagement, and long-term learning. For instance, it was found that participants with VR training identified hazards more accurately and evacuated faster in tunnel evacuation exercise than those who used non-immersive training tools [4]. Likewise, Lovreglio et al. [5] reported that VR training for the PASS (Pull, Aim, Squeeze, Sweep) fire extinguisher technique not only improved participants' procedural knowledge but also increased their confidence and sense of preparedness compared to video instruction. Building on this, Sun et al. [6] integrated serious gaming elements and haptic feedback into a VR program to further enhance users' ability to operate fire extinguishers and select appropriate hydrants.

Augmented reality (AR) has also been explored as a complementary or alternative training approach. Domgue et al. [7] examined the AR-based PASS training and observed that participants were actively engaged throughout the exercise. However, it was not as effective as VR in improving performance or knowledge retention. Paes et al. [8] advanced this work by developing an AR system that guided participants through a series of fire response tasks, including alarm identification, safety vest use, and evacuation procedures. Their study showed that AR can increase knowledge similar to video training at the same time improving motivation and self-confidence. However, this work did not include a VR comparison, omitted extinguisher handling, and was relatively limited in scope.

Evidence of VR's effectiveness extends beyond single-skill instruction. For example, VR-based shipboard fire drills have been shown to improve spatial awareness, equipment recognition, and decision-making under pressure [9][10]. Similarly, VR system was created for a safe and controlled environment evacuation training underground commercial settings [11]. Authors examined how people evacuate and what factors contribute to pre-movement delays insights that would be difficult to capture in real-world situations.

Researchers have also adapted VR to suit participants in different age categories successfully. For instance, Fu and Li [12] developed VR system for older adults, assisting them to respond more accurately in emergency situations. In [13], it was observed that teenagers who trained regularly with VR fire escape simulations continued to improve, though frustration sometimes reduced their confidence. In another example, T and Selvarani [14] used VR to teach fire safety to children with Autism Spectrum Disorder (ASD), showing how flexible technology can be for inclusive education. Still, most of these studies focus on narrow groups and seldom compare their results to non-immersive training, limiting how far the conclusions can be applied.

Despite rapid progress in the field, key research gaps persist. Many VR-based training systems remain confined to single-task activities (e.g., fire extinguisher use, alarm recognition, etc.) without situating these tasks within comprehensive, realistic scenarios. Additionally, numerous studies focus on specialized environments, including tunnels and maritime contexts, or on specific user populations, by this limiting the generalizability of their outcomes. A particularly underexplored area involves VR fire safety training for residents of multi-story apartment buildings, where distinct challenges such as vertical evacuation, inter-floor smoke propagation, and occupant coordination arise. Even within residential studies, most efforts concentrate on targeted populations rather than addressing the broader tenant community.

Table 1. Comparative table of approaches in literature

Study	Mode	Training Focus	Key Findings	Identified Gaps
Ling et al. (2025) [4]	VR	Tunnel-fire evacuation	Faster evacuation times and improved hazard detection	No integration with wearable sensors
Lovreglio et al. (2021) [5]	VR	PASS maneuver	Greater knowledge acquisition, retention, and self-efficacy versus video	Limited to PASS training
Sun et al. (2025) [6]	VR	Fire-extinguisher operation	Enhanced Chinese citizen proficiency with extinguisher use and hydrant selection	Limited to PASS training and proper fire hydrant selection
Domgue et al. (2024) [7]	AR	PASS maneuver	Less effective than VR for PASS	Limited to PASS training
Paes et al. (2024) [8]	AR	Multi-step building evacuation	Equivalent knowledge gains to video, plus higher intrinsic motivation and self-efficacy	No VR comparison; no extinguisher component; narrow task set
Markopoulos & Luimula (2020) [9]	VR	Maritime fire scenarios	High-resolution VR devices improved readability of technical diagrams and detail recognition	Need for evidence-based solutions to prove effectiveness
Pitana et al. (2020) [10]	VR	Maritime fire scenarios	Found VR training reliable, less risky, and cost-effective compared to conventional methods	Future work should focus on methods to minimize motion sickness experienced by some users
Wang et al. (2020) [11]	VR	Underground commercial building evacuation	Effective protocols identified for subterranean egress	Focuses on premovement time rather than fire safety training
Fu and Li (2023) [12]	VR	Fire-safety response in elderly	Tailored scenarios improved elderly participants' response accuracy	VR system was developed for only elderly people
Hong et al. (2023) [13]	VR	Adolescent fire-escape training	Daily VR sessions over three weeks yielded progressive learning	No alternative system comparison
T. & Grace Selvaran (2020) [14]	VR	Fire-safety training for children with ASD	Demonstrated feasibility of VR for ASD populations	No comparison to other training modalities

Given the lack of research on multi-story apartment settings, we propose a novel VR-based fire safety training system specifically designed for apartment residents. The system is developed for VR glasses. The elements such as dynamic fire behaviour, multi-room navigation, and interactive use of firefighting equipment simulates realistic high-rise fire emergencies. One of the advantages of our system is, it is designed for a general audience and is not limited to specific age groups. The challenges of residents in multi-story buildings were addressed in this study. To evaluate the effectiveness of the system, a comparative study against traditional video-based training. Independent variables such as performance rate, knowledge test results, and overall user experience were examined during a simulated fire emergency scenario.

This project was developed in collaboration with representatives of the Ministry of Emergency Situations (MES) of Kazakhstan. It aims to enhance both professional responder preparedness and public fire safety education. The following factor contributed to the novelty of our study:

- Immersive, apartment-specific scenarios that closely replicate realistic emergency conditions to improve engagement and contextual relevance;
- Dynamic fire behavior simulations and responsive user feedback to promote situational awareness and adaptive decision-making;
- Interactive firefighting equipment to reinforce procedural memory, such as the use of fire extinguishers.

Furthermore, this study aims to contribute to the literature by answering the following research questions (RQs).

1) RQ1: Can a VR-based fire safety training system outperform video-based training?

2) RQ2: What is the perception of the user experience for VR training system and its modalities?

The remainder of this paper is organized as follows: Section 2 presents the methodology for evaluating the VR-based fire safety training system. Section 3 details the system implementation, including the software architecture, the construction of the VR environment, and fire behavior simulations. Section 4 discusses the experimental results, and Section 5 concludes the paper by outlining future research directions.

Methodology

We conducted a comparative study that included both immersive VR and conventional video-based instruction in order to evaluate the potential effectiveness of VR-based fire safety training. The three primary phases of the study were preparation, experimentation, and data analysis, as illustrated in Fig. 1.

In order to determine research gaps and formulate research questions, the body of existing literature during the preparation phase was examined. We completed the experimental design and recruited participants after the VR training system was developed.

Participants were randomized to either the VR training group (experimental) or the video-based training group (control) during the experimentation phase. The only distinction between the two groups was the delivery method, however, both received the same fire safety information.

After training, we looked at four important dimensions during the data analysis stage: (1) subjective immersion, measured using the Presence Questionnaire; (2) objective task performance time; (3) task accuracy, assessed via performance rates; and (4) qualitative user feedback, gathered through semi-structured interviews. These evaluation metrics are based on prior studies [4], [5], [13], which emphasize the importance of immersion and procedural understanding in emergency preparedness.

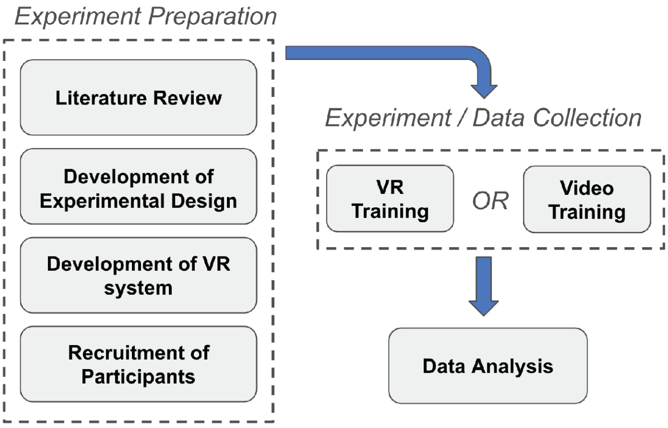

Figure 1. Research: Preparation and tasks for experiment.

System Implementation

The implementation of the VR fire safety training system was divided into distinct phases to ensure functionality, interactivity, and realism. Each component is integrated with Meta Quest Pro hardware to provide an immersive training experience. Advanced physics-based fire behavior and suppression mechanics were incorporated to enhance realism and effectiveness in emergency response training.

Hardware and Software Platforms

The proposed VR simulation is deployed on the Meta Quest Pro headset, taking advantage of its advanced tracking capabilities and high-resolution display to improve immersion [15]. A detailed breakdown of its internal architecture can be seen in Fig. 2, which illustrates key elements such as sensors, display modules, and controllers.

The headset's integrated sensors—including inertial measurement units (IMUs) and outward-facing cameras—enable precise 6-degree-of-freedom (6DoF) tracking, ensuring realistic user movements within the virtual environment. The eye-tracking cameras further optimize rendering efficiency by employing foveated rendering. The high-resolution LCD display modules (1800 × 1920 pixels per eye) further enhance immersion by delivering crisp visuals. Ergonomic controllers provide accurate haptic feedback, simulating realistic tactile responses.

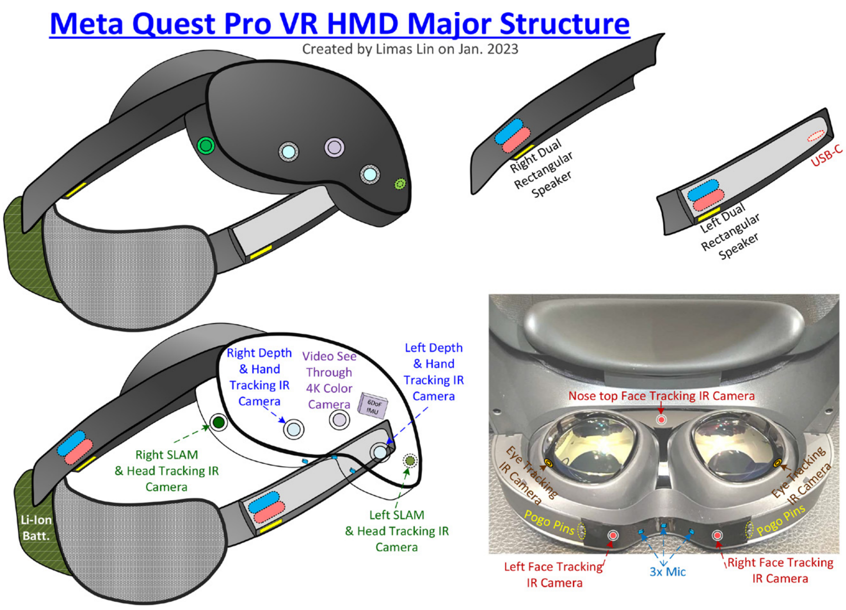

Figure 2. Breakdown of Meta Quest Pro headset components [6].

Scientific Journal of Astana IT University
ISSN (P): 2707-9031 ISSN (E): 2707-904X
VOLUME 23, SEPTEMBER 2025

The system is compatible with latest firmware to ensure optimal performance and minimal motion-tracking latency. VR headsets can significantly improve safety training by increasing engagement, knowledge retention, and responsiveness to emergency situations [16]. Wearable VR can trigger faster reactions to hazards than conventional training [17]. It was found that Unity's physics engine improves the realism of emergency training [18]. Its advanced rendering and physics models contribute to the accuracy of fire spread simulations [19].

The simulation was developed in Unity 6000.0.33f1 Long-Term Support (LTS) [20] (Code available on GitHub). Third-party assets and Unity built-in packages were integrated into the system architecture. From the Unity Asset Store, the Free Fire VFX – URP (v1.0.2023) package was imported to generate realistic fire and smoke effects optimized for the Universal Render Pipeline (URP). the Meta XR All-in-One SDK (v72.0.0) was imported to ensure compatibility with HMD and to enable features such as spatial awareness and hand interaction [21].

Several of Unity's built-in packages were also incorporated to extend functionality and streamline development. The AI Navigation (v2.0.5) module supports intelligent pathfinding and agent-based behaviors and Test Framework (v1.4.5) provides tools for automated testing for reliability and stability of user interactions. The Timeline (v1.8.7) package enables cinematic sequencing and precise control over time-based animations, which are essential for creating engaging and instructional narrative content.

To support users without advanced programming skills, Visual Scripting (v1.9.5) was used to enable node-based scenario creation, making interactive design more accessible. The XR Interaction Toolkit (v3.0.7) was a tool for handling core VR interactions, including hand tracking, object manipulation, and locomotion [22]. XR Plugin Management (v4.5.0) facilitated streamlined XR hardware integration and ensured consistent performance across supported VR devices.

Environment and Asset Integration

The demonstrative simulation environment is designed to replicate a multi-story apartment complex, reflecting common residential settings where fire safety training is crucial (see Fig. 3). The image shows the evacuation zone, a room equipped with a fire extinguisher, residential rooms, and non-player characters. These elements are incorporated to create a comprehensive and realistic virtual training environment, enhancing the immersion and effectiveness of fire safety training.

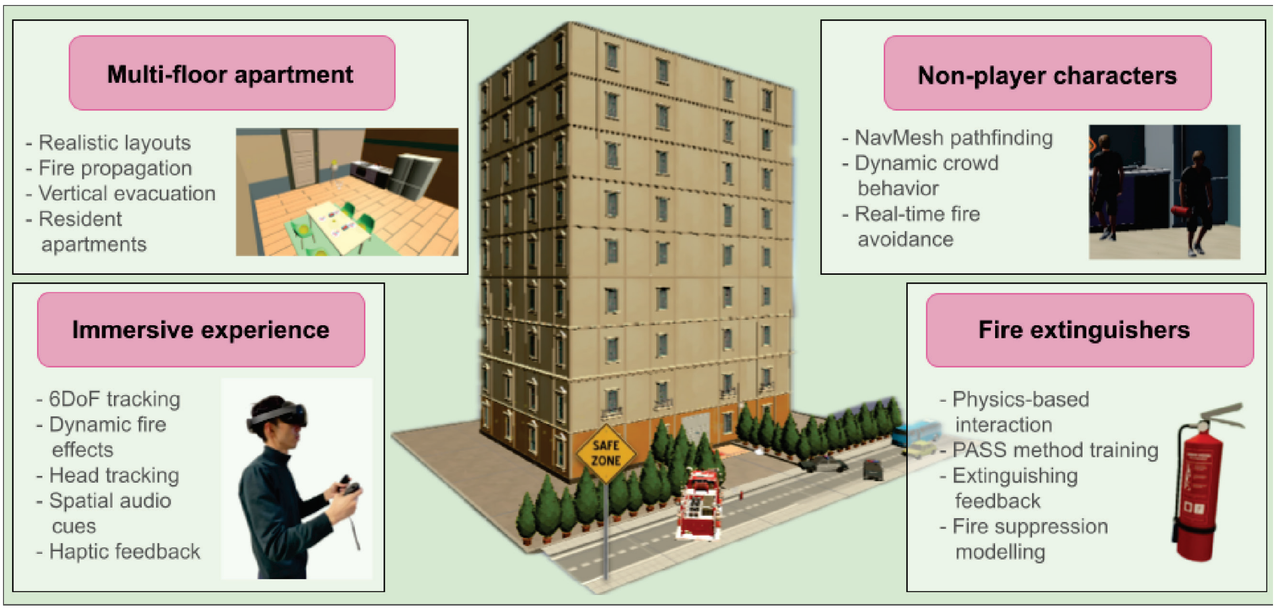

Figure 3. Overview of the VR-based training system.

DOI: 10.37943/23LTJV6054

Fire Simulation and Scripting

Fire Initiation and Spread Mechanism, a physics-based model simulates realistic fire spread, with dynamic propagation influenced by environmental factors and material properties. The spread is governed by a heat diffusion equation with suppression effects:

$$\partial F/\partial t = \alpha \nabla^2 F - \beta E(x, y, t) F \tag{1}$$

where $F(x,y,t)$ is the fire intensity at location (x,y) and time t, α is the fire diffusion coefficient, β is the suppression efficiency, and $E(x,y,t)$ represents the extinguisher's effect over space and time (1).

– Fire Initiation Script: A custom C# script, initializes the fire outbreak at a predefined random ignition point.

– Fire Propagation Algorithm: Upon ignition, the system computes a fire spread radius around the source. Within this radius, up to five flammable objects (configurable via the Unity Editor) are selected to ignite. The fire propagation logic is implemented in Unity as shown in the following pseudocode:

```
If fire is not currently spreading OR the maximum spread count has been reached:
    Exit the procedure
Get all colliders within spreadRadius of the current position
For each collider in the result:
    If the collider's transform equals self:
        Skip to the next collider
    If the object has a FireSpread component:
        Calculate delta = diffusionRate × (intensity - neighbor.intensity) × Δt
        Apply delta to the neighbor via ReceiveHeat(delta)
    If the object has a FlammableObject component and is not burning:
        Call IgniteWithDelay(0) on the flammable object
        Increment currentSpreadCount
        If currentSpreadCount ⩾ maxSpreadCount:
            Exit the loop
Schedule this procedure to run again after a specified delay
```

Fire Suppression System

Environment and Asset Integration

The physics-based fire suppression system allows users to interact with a realistic virtual extinguisher, which includes functional components like a safety pin, handle, and nozzle.

The fire extinguisher simulation incorporates realistic components, including a safety pin, handle, and nozzle, to enhance user immersion in VR environment. A particle system dynamically simulates the release of extinguishing agents, such as CO_2 or dry chemical, with physics-based parameters governing dispersion and behavior. The suppression mechanism relies on a thermal model where flames are extinguished once the temperature of affected objects drops below a critical threshold, ensuring an accurate representation of fire dynamics.

$$\partial T/\partial t = -\gamma S(x, y, t) \tag{2}$$

where $T(x,y,t)$ is the object's temperature, γ is the cooling efficiency constant, and $S(x,y,t)$ is the suppressant's intensity at that location (2).

User interaction is facilitated through the *XR Interaction Toolkit*, allowing participants to intuitively grab, handle, and operate the extinguisher. Removing the safety pin and pressing the handle activates the suppressant release, while real-time nozzle tracking enables precise directional aiming. The extinguishing effectiveness is determined by physics-driven factors,

Scientific Journal of Astana IT University
ISSN (P): 2707-9031 ISSN (E): 2707-904X
VOLUME 23, SEPTEMBER 2025

including distance, angle, and flow intensity, ensuring that fire suppression responds realistically to user actions. This approach not only enhances training fidelity but also reinforces proper firefighting techniques in a controlled virtual setting.

Environment and Asset Integration

The *XR Origin* system integrates the VR camera to ensure that head movements are accurately reflected in the virtual environment. This setup is based on the latest version of the *XR Interaction Toolkit* (version 2.1.0 or later), which enables precise head tracking and spatial navigation.

User interactions in the VR environment are managed through Unity's input system. The right joystick controls rotational movement along the X-axis, while the left joystick allows free navigation within the virtual environment. Fig. 4 illustrates the controller layout and the input mappings used for navigation and interaction.

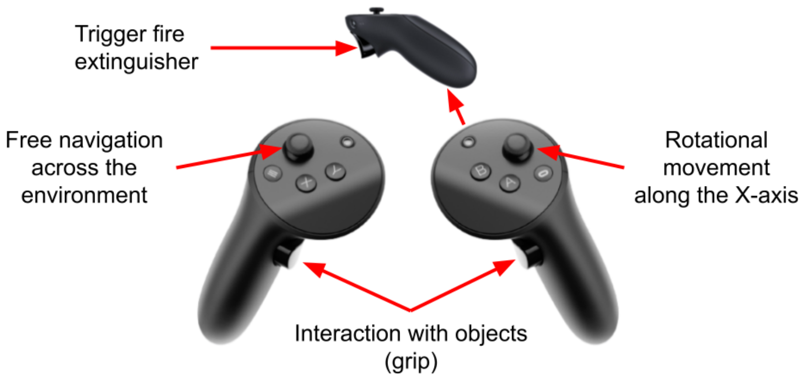

Figure 4. Button layout of the Meta Quest Pro controller for different interactions

The simulation supports natural interactions such as grasping and manipulating objects. Doors can be opened using the index-finger trigger, activating a physics-based hinge rotation, as illustrated in Fig. 5.

Figure 5. Interactions with a door using the index-finger trigger to activate hinge rotation.

DOI: 10.37943/23LTJV6054

NPC Navigation

Navigation Mesh and NPC behavior simulates human behavior in fire evacuations using Unity's NavMesh framework, enabling dynamic pathfinding and realistic responses to obstacles and fire spread.

Unity's NavMesh system generates a navigation grid for realistic movement, while a dynamic pathfinding algorithm allows NPCs to adapt evacuation routes in response to fire spread and environmental changes. As shown in the following pseudocode, the NPC continuously updates its path to avoid obstacles and fire.

```
Initialize NPC position and assign target exit
Load NavMesh and generate walkable navigation surface
while NPC has not reached the designated exit do
    Compute path to target exit using NavMesh
    if path is valid then
        Move NPC along the computed path
        if fire or obstacle is detected along the path then
            Recalculate path to the nearest safe exit
        end if
    else
        Log error: no valid path found
    end if
end while
Mark evacuation as complete
```

Experimental Design

Rationale for Experiments

Several studies in the literature have explored the impact of different sensory modalities on performance during fire-related emergencies. For instance, it was shown that VR simulations facilitated faster evacuation and improved hazard detection in [4]. However, their system did not incorporate multisensory or wearable elements. Our system integrates visual, auditory, and haptic cues to enhance realism and user engagement. This multimodal approach has the potential to better simulate real emergency conditions and support more effective training outcomes.

To evaluate the effectiveness of different warning modalities in an AR-based fire safety training system, we selected four key metrics: presence questionnaire, escape time, performance rate, knowledge test, and semi-structured interviews (see Fig. 6). Presence questionnaire [23] is used to assess the user's subjective sense of immersion. This is important because prior work by Hong et al. [13] found that a stronger sense of presence correlates with improved engagement and learning in immersive fire safety training. Escape time measures how quickly participants respond to simulated fire scenarios and evacuate the building. Performance rate measure how well participants follow correct procedures under different warning conditions. This complements previous work such as Lodvreglio et al. [5], where knowledge acquisition was assessed as key training outcomes. The knowledge test, composed of both multiple-choice and open-ended questions. It measures participants' understanding and retention of essential fire safety procedures after training. Semi-structured interviews were conducted to examine user perceptions, preferences, and mental workload. These metrics allow for a comprehensive evaluation of both behavioral performance and user experience.

Scientific Journal of Astana IT University
ISSN (P): 2707-9031 ISSN (E): 2707-904X
VOLUME 23, SEPTEMBER 2025

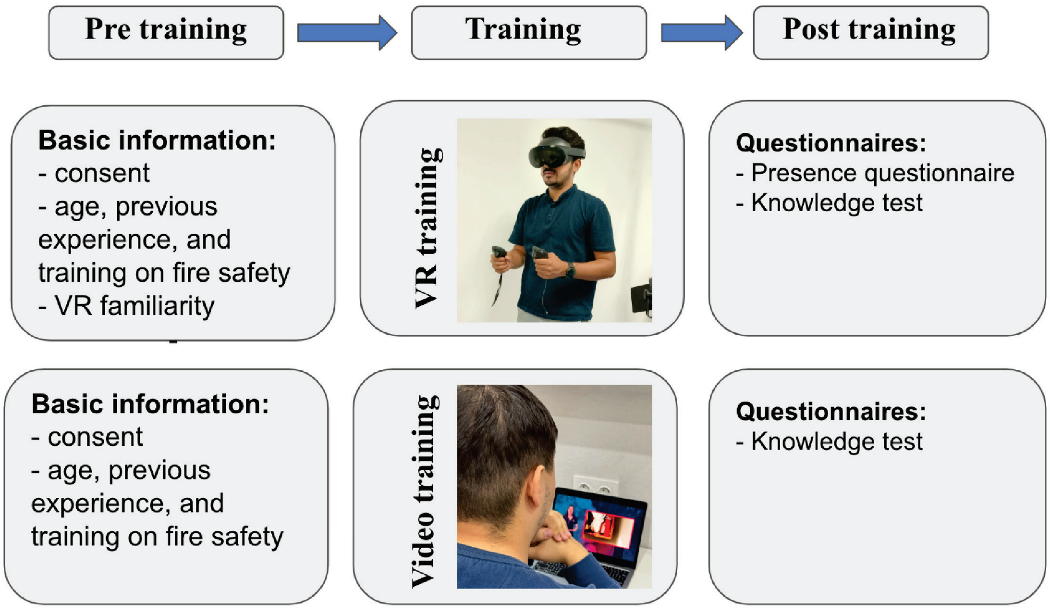

Figure 6. Research procedure for control (video) and experimental (VR) groups.

Participants

20 participants were recruited for our experiment. We divided participants into equal two gender balanced groups: control and experimental groups. Control group participants received conventional video-based instruction whilst VR-based training was utilized in the experimental group. The mean age of the participants was 29.8 (SD=0.63), and only a couple of them were familiar with AR/VR technology in experimental group. During the experiment, three of the participants wore VR glasses with eyeglasses underneath.

Experimental Scenario

The VR-based fire safety training begins with a fire outbreak on the second floor of building. Participants must quickly assess the situation and respond appropriately by identifying hazards and taking immediate action. This includes attempting to contain small fires using virtual extinguishers with proper PASS method techniques while managing smoke propagation through door control. The participants came to the experimental site for one session and performed the tasks.

Before beginning the VR training, experimenters assisted each participant in fitting and adjusting the VR headset, ensuring both proper visual calibration and wearer comfort. Once this familiarization phase was complete, participants individually entered a high-fidelity VR environment replicating a residential fire. Upon initiation of the fire stimulus, each participant was instructed to respond naturally, without further prompts. Observers recorded whether the participant located (C1) and activated the fire alarm (C2), retrieved and discharged the portable extinguisher, executed a full sweep of the nozzle at the fire's base (C3), chose the stairwell rather than the elevator for evacuation (C4), and proceeded to a predefined safe-zone assembly area outside the building (C5). Each of these five actions was treated as a binary "performed/not performed" checkpoint, capturing which critical safety behaviors occurred in a single run through the scenario.

As the scenario develops, participants activate alarm systems to notify NPCs and coordinate evacuation procedures. They must navigate through hazardous conditions including blocked exits and spreading flames while guiding NPCs to safety. If participants fail to manage the emergency properly, the simulation restarts with instructional feedback to reinforce correct safety protocols. In the experiment, we hypothesized that the VR training system would be beneficial for fire safety training.

Results and Discussion

Participants engaged in training scenarios that required them to identify fire hazards, locate emergency exits, execute evacuation protocols, and navigate safely to the designated safe zone. All participants successfully reached the safe zone; however, two required three attempts to complete the navigation correctly, while other participants accomplished all tasks flawlessly on the first attempt. Post-experiment feedback highlighted that participants found the training to be highly interactive, with the inclusion of NPCs enhancing situational awareness. However, participants noted limitations regarding the system's environmental realism. In the semi-structured interview, one participant also reported experiencing headaches due to rapid movements in the virtual environment.

Participants applied fire safety knowledge effectively in the interactive VR environments. Overall, the integration of dynamic fire simulations and NPC-driven interactions contributed to a more engaging and effective training experience. While the Meta Quest Pro's advanced tracking enabled immersive interactions, its eye-tracking capabilities remained underutilized in the current implementation. Future iterations could leverage this feature for gaze-based hazard detection assessments.

Participant performance was assessed using a structured rubric (see Table 2), which included both multiple-choice (Q1–Q3) and open-ended questions (Q4–Q9). The multiple-choice items, each worth one point, evaluated immediate recall of essential fire safety actions such as evacuation protocol and fire extinguisher use.

The open-ended questions were graded on content accuracy and completeness. For instance, full credit (2 points) in Question 4 was awarded to participants who correctly listed and briefly explained all four PASS steps (Pull, Aim, Squeeze, Sweep). Partial credit (1 point) was given for identifying 2–3 correct steps, while incomplete or incorrect responses received no points. Similarly, Questions 5–9 assessed conceptual understanding, with full credit given for specific and accurate information (e.g., identifying fire risks associated with elevators or specifying a designated assembly point). Responses with general or partially correct ideas received one point, and incorrect or blank responses received zero.

This grading approach balanced factual recall with applied understanding of fire safety procedures. On average, participants in the video training group scored 7.3 (SD = 1.33), while those in the VR training group scored 10.9 (SD = 2.37), suggesting improved performance and retention in the VR condition (see Fig. 7).

Scientific Journal of Astana IT University
ISSN (P): 2707-9031 ISSN (E): 2707-904X
VOLUME 23, SEPTEMBER 2025

Table 2. Knowledge test questions

No	Question (with Type)	Scoring Criteria
Q1	MCQ – What is the correct order of actions when discovering a fire?	Correct sequence (Trigger alarm → Attempt to extinguish if safe → Evacuate) = 1; Incorrect order = 0
Q2	MCQ – Where should you aim the nozzle of a fire extinguisher?	Base of the flames = 1; Any other answer = 0
Q3	MCQ – Which route should you take when evacuating a building during a fire?	Stairs = 1; Any other answer = 0
Q4	Open – List and briefly describe the steps of the PASS method for operating a fire extinguisher.	Names and briefly explains all 4 steps (Pull, Aim, Squeeze, Sweep) = 2; Names at least 2 steps correctly = 1; Fewer or incorrect = 0
Q5	Open – Why is it unsafe to use elevators during a fire evacuation? Maximum points - 2	Mentions specific dangers such as electrical failure, smoke infiltration, loss of power, or entrapment = 2; Mentions "elevator might stop working" = 1;
Q6	Open – Explain why activating the fire alarm quickly is essential during a fire emergency. Maximum points - 2	Explains it alerts others and enables a faster emergency response = 2; Mentions only "to warn people" or "notify" without purpose = 1; Unclear or incorrect = 0
Q7	Open – After evacuating, what type of location should you choose to wait safely?	States "designated assembly point," "meeting point," or "open area away from building" = 2; States only "outside" or "away from fire" = 1;
Q8	Open – How did the training help you remember and understand the correct fire safety procedures?	Describes specific procedures learned or how training improved recall or confidence = 2; Training was useful without naming procedures = 1; Off-topic or blank = 0
Q9	Open – If you had to teach someone else what you learned, what one key point would you emphasize most?	Identifies a specific, critical procedure (e.g., activate alarm, use PASS, do not use elevator) = 2; Mentions safety generally without specifics = 1; Irrelevant = 0

Participants completed the presence questionnaire, which included five subscales: Realism, Possibility to Act, Quality of Interface, Possibility to Examine, and Self-Evaluation of Performance. The mean total presence score in our study was 108.5 (SD = 0.94), which is slightly above the French normative mean of 104.39 (SD = 18.99), suggesting a generally high sense of presence among participants [23] (see Table 3).

Table 3. Results of Presence Questionnaire

Subscale	Mean (Our Study)	SD	Normative Mean	Normative SD
Realism	39.8	0.81	29.45	12.04
Possibility to Act	23.9	0.82	20.76	6.01
Quality of Interface	15.5	1.11	15.37	5.15
Possibility to Examine	17.8	0.7	15.38	4.9
Self-Evaluation of Performance	11.5	1.06	11	2.87

The ***Realism*** subscale (M = 39.8, SD = 0.81) exceeded the French norm (M = 29.45, SD = 12.04), suggesting the virtual environment was perceived as highly lifelike. The "***Possibility to Act***" score (M = 23.9, SD = 0.82) was also higher than the norm (M = 20.76, SD = 6.01), indicating a strong sense of interactivity and control. The "Quality of Interface" score (M = 15.5, SD = 1.11), which included reverse-scored items, aligned closely with the norm (M = 15.37, SD = 5.15), reflecting a generally usable interface. For “***Possibility to Examine***”, participants scored 17.8 (SD = 0.70), above the normative mean of 15.38 (SD = 4.90), suggesting high exploratory freedom. The “***Self-Evaluation of Performance”*** score (M = 11.5, SD = 1.06) was slightly above the norm (M = 11.00, SD = 2.87), indicating moderate confidence in task performance. Overall, all subscales scored above their respective normative means, supporting the effectiveness of the VR system in eliciting a strong sense of presence.

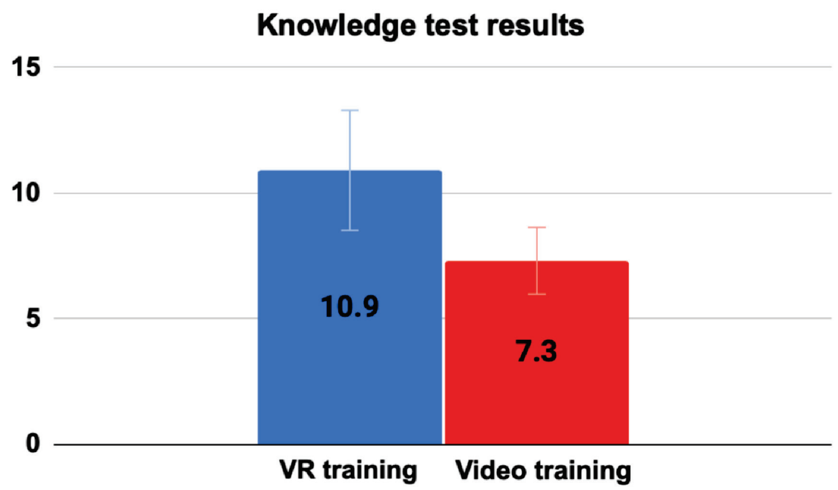

Figure 7. Knowledge Test Results.

The overall mean escape time was 1 min 57 s (SD = 4 s). Male participants completed the escape in 1 min 53 s (SD = 3 s), which is 9 s faster than female participants (2 min 02 s, SD = 4 s).

Every participant ultimately reached the safe-zone, yielding a 100 percent performance rate for that criterion. Stair-based evacuation was also flawless, with all participants choosing the stairs. Extinguisher deployment was attempted by nine out of ten participants (90 percent), while seven participants (70 percent) completed an effective suppression sweep. Alarm activation similarly reached 70 percent compliance, as seven participants remembered to pull the alarm before proceeding. The five binary checkpoints produced an average score of 4.2 out of 5 (SD = 0.8). Although only 70% activated the alarm or completed the suppression sweep, most participants successfully performed 4 or more tasks, raising the overall average. These results indicate that, although VR training reliably conveys evacuation and safe-zone procedures, additional emphasis on early alarm signalling and correct suppression technique may further enhance overall fire-safety performance.

To conclude, the results of this study underscore the effectiveness of VR-based fire safety training in enhancing both procedural knowledge and user engagement. Participants demonstrated strong performance in critical safety tasks, high knowledge retention, and reported a strong sense of presence within the virtual environment, as confirmed by both quantitative metrics and qualitative feedback. The training system successfully conveyed essential emergency procedures, with particularly high success in evacuation and hazard navigation. Nevertheless, the findings also reveal areas for improvement, including increasing attention to alarm activation and extinguisher use. Overall, the integration of immersive simulation, NPC interaction, and structured assessment tools offers a promising approach to advancing fire safety education through virtual reality.

Conclusion

The VR-based fire safety training system was developed to enhance emergency preparedness among apartment residents by providing an interactive and risk-free learning environment. The results indicate that the VR-based training outperformed video-based instruction (RQ1), with significantly higher knowledge scores and greater user engagement. Participants demonstrated strong overall performance in critical tasks such as evacuation and hazard navigation, and reported a high sense of presence, especially in dimensions like realism and interactivity. However, some participants did not activate the alarm or complete the suppression technique correctly, highlighting areas where additional emphasis is needed. The perception of the user experience for the VR training system and its modalities was largely positive, with participants reporting high engagement with the VR training (RQ2). The mean total presence score of 108.5 (SD=0.94) was slightly above the French normative mean, suggesting a generally high sense of presence. Subscales such as "Realism" and "Possibility to Act" scored particularly well, indicating that the virtual environment was perceived as highly lifelike and offered a strong sense of interactivity and control. The dynamic fire simulations and NPC-driven interactions were found to contribute to a more engaging and effective training experience. However, participants did note limitations concerning environmental realism and one reported motion-related discomfort (headaches) due to rapid movements. Additionally, the eye-tracking capabilities of the Meta Quest Pro were underutilized in the current implementation. Future developments should prioritize enhancing environmental realism to address participant feedback, better utilizing the eye-tracking capabilities of the Meta Quest Pro for gaze-based hazard detection, and optimizing movement mechanics to reduce motion-related discomfort. Follow-up studies will systematically evaluate these enhancements, focusing on user experience, system usability, and their impact on fire safety knowledge retention and emergency response performance.

References

[1] Jain, A. (2024). Examining the use of virtual reality (VR) technology in health and safety training within hazardous work environments: A scoping review. *Open Repository AUT*. https://openrepository.aut.ac.nz/server/api/core/bitstreams/4383287d-66ee-4f7c-aece-af5fc4094c55/content

[2] Burdea, G.C., & Coiffet, P. (2003). Virtual Reality Technology. *Presence: Teleoperators & Virtual Environments*, 12, 663–664.

[3] Contini, G., Grandi, F., & Peruzzini, M. (2025). Human-Centric Green Design for automatic production lines: Using virtual and augmented reality to integrate industrial data and promote sustainability. *Journal of Industrial Information Integration*, 44, 100801. https://doi.org/10.1016/j.jii.2025.100801

[4] Ling, J., Li, X., Shen, Y., Chen, C., Yan, Z., Zhu, H., & Li, H. (2025). Human centric VR system development supporting fire emergency evacuation: A novel knowledge-data dual driven approach. *Expert Systems with Applications*, 273, 126895. https://doi.org/10.1016/j.eswa.2025.126895

[5] Lovreglio, R., Duan, X., Rahouti, A. & others. (2021). Comparing the effectiveness of fire extinguisher virtual reality and video training. *Virtual Reality*, 25, 133–145. https://doi.org/10.1007/s10055-020-00447-5

[6] Sun, L., Lee, B. G., & Chung, W. (2024). Enhancing Fire Safety Education Through Immersive Virtual Reality Training with Serious Gaming and Haptic Feedback. *International Journal of Human-Computer Interaction*, 1–16. https://doi.org/10.1080/10447318.2024.2364979

[7] Domgue, S., Faiola, A., & Gale, B. (2023). Effectiveness of augmented reality in PASS fire extinguisher training: A comparative study. *Journal of Safety Research*, 76, 182–190.

[8] Paes, D., Feng, Z., King, M., Shad, H. K., Sasikumar, P., Pujoni, D., & Lovreglio, R. (2024). Optical see-through augmented reality fire safety training for building occupants. *Automation in Construction*, 162, 105371. https://doi.org/10.1016/j.autcon.2024.105371

[9] Markopoulos, E., & Luimula, M. (2020). Immersive Safe Oceans Technology: Developing virtual onboard training episodes for maritime safety. *Future Internet*, 12(5), 80. https://doi.org/10.3390/fi12050080
[10] Pitana, T., Prastowo, H., & Mahdali, A. P. (2020). The Development of Fire Safety Appliances Inspection Training using Virtual Reality (VR) Technology. *IOP Conference Series: Earth and Environmental Science*, 557(1), 012064. https://doi.org/10.1088/1755-1315/557/1/012064
[11] Wang, D., Zhou, T., & Li, X. (2020). Impacts of environment and individual factors on human pre-movement time in underground commercial buildings in China: a Virtual Reality–Based study. *ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems Part A: Civil Engineering*, 7(1). https://doi.org/10.1061/ajrua6.0001112
[12] Fu, Y., & Li, Q. (2023). A virtual Reality–Based serious game for fire safety behavioral skills training. *International Journal of Human-Computer Interaction*, 40(19), 5980–5996. https://doi.org/10.1080/10447318.2023.2247585
[13] Hong, J., Chan, H., Teng, Y., Tai, K., & Lin, C. (2023). VR training program for fire escape: Learning progress predicted by the perception of fire presence, VR operational frustration, and gameplay self-efficacy. *Computers & Education X Reality*, 3, 100029. https://doi.org/10.1016/j.cexr.2023.100029
[14] T, N. S., & Selvarani, A. G. (2020). Virtual Reality based System for Training and Monitoring Fire Safety Awareness for Children with Autism Spectrum Disorder. *2022 6th International Conference on Devices, Circuits and Systems (ICDCS)*, 26–29. https://doi.org/10.1109/icdcs48716.2020.243541
[15] Meta. (2023). *Meta Quest Pro technical specifications*. Oculus Developer. https://developer.oculus.com/
[16] Einloft, J., Meyer, H. L., Bedenbender, S., Morgenschweis, M. L., Ganser, A., Russ, P., Hirsch, M. C., & Grgic, I. (2024). Immersive medical training: a comprehensive longitudinal study of extended reality in emergency scenarios for large student groups. *BMC Medical Education*, 24(1). https://doi.org/10.1186/s12909-024-05957-3
[17] Berthiaume, M., Kinateder, M., Emond, B., Cooper, N., Ishika Obeegadoo, & Lapointe, J.-F. (2024). Evaluation of a virtual reality training tool for firefighters responding to transportation incidents with dangerous goods. *Education and Information Technologies*. https://doi.org/10.1007/s10639-023-12357-5
[18] Zhao, X., Bian, Y., & Zhang, Y. (2025). Sustainable development through dynamic emergency evacuation signage: A BIM- and VR-based analysis of passenger behavior. *Sustainability*, 17(6), 2626. https://doi.org/10.3390/su17062626
[19] Narciso, D., Melo, M., Raposo, J. V., Cunha, J., & Bessa, M. (2019). Virtual reality in training: an experimental study with firefighters. *Multimedia Tools and Applications*, 79(9-10), 6227–6245. https://doi.org/10.1007/s11042-019-08323-4
[20] Unity Technologies. (2025). Unity 3D Engine – Long-Term Support (LTS) documentation. https://unity.com/releases/lts
[21] Meta. (2023). *Meta XR All-in-One SDK*. Oculus Developer. https://developer.oculus.com/documentation/unity/meta-xr-all-in-one-sdk/
[22] Unity Technologies. (2023). *XR Interaction Toolkit: VR and AR interaction system*. https://docs.unity3d.com/Packages/com.unity.xr.interaction.toolkit@2.1/manual/index.html
[23] Witmer, B. G., & Singer, M. J. (1998). Measuring presence in virtual environments: a presence questionnaire. *PRESENCE Virtual and Augmented Reality*, 7(3), 225–240. https://doi.org/10.1162/105474698565686