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Virtual Reality Simulations for Effective Fire Safety Training in Passenger Trains

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Abstract

Ensuring safety in railway operations, particularly during fire incidents, is crucial given the unique challenges posed by passenger train layouts. Traditional training methods, while common, often result in unrealistic outcomes and incur high costs. This article proposes a shift towards using virtual reality (VR) serious games as an innovative training tool for railway professionals. To pursue this objective, a Serious Games (SGs) prototype was developed using Unity3D. This approach provides trainees with an immersive platform to interact within a realistic virtual environment, allowing them to practice and refine fire safety procedures tailored to the dynamic and challenging contexts of rolling stock environments. A preliminary prototype was tested with 30 participants, and the initial results demonstrated the simulator's practicality and effectiveness. The findings suggest that VR-based training can significantly enhance fire safety preparedness in the railway industry. The article concludes by advocating for further research and development to fully realize the potential of this cutting-edge training approach.

Keywords: *fire, training, passenger train, virtual reality, serious game.*

1 Introduction

The occurrence of a fire aboard rolling stock is undeniably distressing, with repercussions extending beyond material destruction to impact the well-being of passengers. Mitigating and minimizing such hazardous circumstances necessitates meticulous planning and comprehensive training. In response to this concern, emergency plans are implemented, outlining appropriate actions for various scenarios. These safety measures are integrated

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into emergency procedures, often requiring simulation drills for practice. However, due to their high cost and time demands, these drills occur only once a year, limiting participation and accessibility for a significant portion of personnel. The substantial expenses associated with training for fire safety on trains using real experimental contexts [1], coupled with constraints on practicing in unconventional and potentially hazardous situations, underscore the urgency to explore innovative strategies. Using virtual reality technologies is one promising option [2-4]. Simulations provide an economical and adaptable way to imitate various situations and instruct experts on suitable reactions.

Serious games refer to computer or smart device games used for purposes beyond entertainment [5]. Clark C. Abt was the first to use the word in 1970 [6]. According to Connolly et al. [7], SGs are video games that are primarily made for educational and training purposes rather than for amusement. Compared to conventional methods of education, it is suggested that participation in SGs can lead to more effective knowledge acquisition and retention [8].

Another technology that enhances the immersive potential of SGs is Virtual Reality (VR). According to its definition, virtual reality (VR) is a "real or simulated environment in which the perceiver experiences telepresence", which is the sensation of being present in an environment via a communication medium [9].VR enables participants to be completely immersed in virtual environments, offering heightened engagement and perception compared to videos [10]. The combination of VR and SGs encourages participants to retain knowledge for extended periods due to the deep engagement, heightened emotional involvement, and physiological arousal they experience [11]. As a result, there is a growing interest in the literature, as well as in recent research endeavors and initiatives, in using VR and SGs to enhance learning. The use of virtual reality serious games is increasingly prevalent in safety training. These games offer several potential advantages, including supporting repetitive training actions, facilitating a better understanding of new situations, and providing easily accessible training with minimal risks and minimal environmental impact [12-13]. Previous research has identified various contexts in which VR and SGs safety training have been applied, including fire evacuation emergencies [13-16], disaster evacuation [17], and earthquake evacuation [18].

In addition to evacuation training, there are other associated investigations within VR SGs-based safety education, such as safety operations training [19-22]. According to Yiqing. Z & Nan. L [23], previous studies have made substantial progress in utilizing VR/SGs for emergency management within built environments, including locations like schools, smart cities, railway stations, hospitals, and more. Despite the advancements in VR and SGs for safety training, the exploration of these technologies in the domain of transportation environments, particularly on board rolling stock, has been limited. A noteworthy area that has received relatively little attention is the development of a virtual training system tailored for trainees involved in fire safety activities aboard passenger trains. This gap highlights the need for innovative approaches to address the unique challenges of fire safety training within the dynamic setting of passenger train operations.

The purpose of this study is to develop and evaluate a VR-based serious game designed to train railway personnel in fire safety protocols. By providing an immersive and interactive training environment, the study aims to enhance the preparedness and response capabilities of train conductors in high-risk scenarios, ultimately improving overall safety in railway operations. Following this initial presentation and the drive toward the core subject of this study, the rest of this manuscript is structured subsequently. The purpose of Section 2 is to introduce the suggested prototype designed to train rolling stock personnel in effectively

managing critical scenarios, such as fire incidents. Section 3 is organized to cover both the experimental setup and the presentation of specific outcomes. Ultimately, in Section 4, conclusions are drawn, and attention is directed towards forthcoming undertakings and advancements.

2 Method

To achieve the outlined objective, a Serious Games prototype was implemented using Unity3D. This strategic approach aimed to provide a comprehensive platform for trainees to not only immerse themselves in lifelike situations but also actively interact within a meticulously crafted virtual environment.

The primary focus of this immersive experience is to allow trainees to practically apply and refine their fire safety procedures, specifically tailored to the dynamic and challenging contexts encountered in rolling stock environments. Through the integration of Unity3D, a dynamic and effective training tool has been created, going beyond traditional methods and offering a hands-on and realistic training experience for train conductors in the realm of fire safety aboard trains. The upcoming sections elucidate the design of key elements in the developed prototype aimed at training environments. These elements encompass the selection of the game engine, the virtual environment, the technique for VR navigation, the narratives, and the intended learning outcomes.

2.1 Game engine

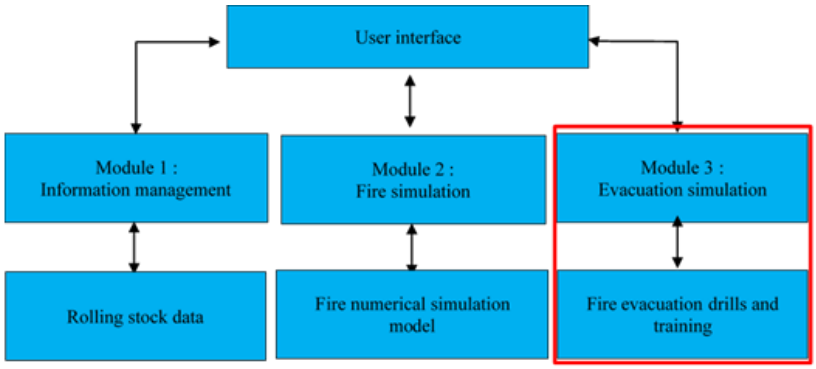
A game engine serves as a framework that facilitates the development of games by enabling various aspects such as importing assets from external software, constructing scenes with these assets, incorporating visual effects, and implementing game logic into the application. Various game engines have been utilized in the creation of Serious Games tools or games, with the choice depending on the specific characteristics and features required for the SGs [24]. The selection of the Unity game engine for the proposed Virtual Reality (VR) Serious Game was motivated by its notable efficiency in both time and cost aspects during the development of VR Serious Games. Unity's prominence stems from its broad accessibility, providing free licenses for academic and non-commercial purposes. Beyond its accessibility, Unity is celebrated as one of the most user-friendly engines, boasting built-in VR support, an extensive array of tutorial resources, and a robust community network.

What sets Unity apart is its adaptability, accommodating various development approaches, including visual coding and traditional scripting. In the creation of the prototype, C# scripts were strategically employed to govern user interactions within the simulated environment and seamlessly manage in-game events throughout the simulation. This utilization of Unity, coupled with the flexibility offered by C# scripting, not only streamlined the development process but also enhanced the overall user experience, making the VR Serious Game more accessible and effective for trainees in the context of fire safety training for railway professionals.

2.2 Architecture of the system

Figure. 1 illustrates the system architecture and the graphical user interface (GUI), which consists of three key components: the information management module, the fire simulation module, and the emergency evacuation simulation module.

Figure. 1. Architecture of the system



The information management module is intended to provide essential rolling stock data, supporting a comprehensive understanding of train-related information. The fire simulation module is designed to create immersive virtual scenarios that realistically depict fire incidents within train environments. The emergency evacuation simulation module facilitates evacuation drills, training, and evaluation of passenger responses during emergencies, contributing significantly to safety preparedness.
It is important to note that, at this stage, only the emergency evacuation simulation module (Module 3) has been developed and implemented. The other two modules remain in the conceptual phase and are planned for future development. This paper therefore presents a partial prototype of the overall system, with a focus on demonstrating the feasibility and functionality of the emergency evacuation component. Future work will expand the system to include the remaining modules, following a phased development approach.

2.2 Virtual environment

In the process of setting up the virtual environment, the study utilized an existing commercially available 3D model [25]. This particular 3D model aligned seamlessly with the conceptualization of developing a virtual reality serious game tailored for a rolling stock environment. To implement this model into the development environment, the procedure outlined in Fig. 2 was followed, which involved the importation of the selected 3D model into the Unity game engine. This step-by-step approach ensured the integration of the chosen model into the Unity framework, facilitating the creation of a realistic and immersive virtual environment for the subsequent stages of the study. The passenger train is comprised of 2 coaches, as illustrated in Figure. 3.

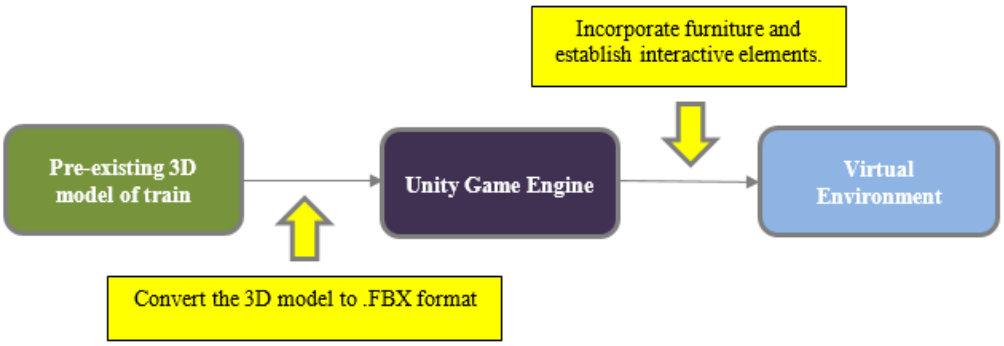


Figure 2. Process diagram outlining the steps involved in crafting the environment

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- **Figure 3**. Image captured within an outdoor space
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Additional elements integrated into the game, including an extinguisher, phone, and fan control knob, were added to offer interactive functionalities. This intentional design empowers users to actively interact with these objects, thereby enhancing the overall learning experience and facilitating the attainment of educational objectives throughout the gameplay. Moreover, triggers have been strategically embedded into the virtual environment, serving to identify user presence in designated areas.

Fig. 4 provides a visual representation of scenes showcasing these interactive objects, illustrating their role in the immersive and educational aspects of the serious game.

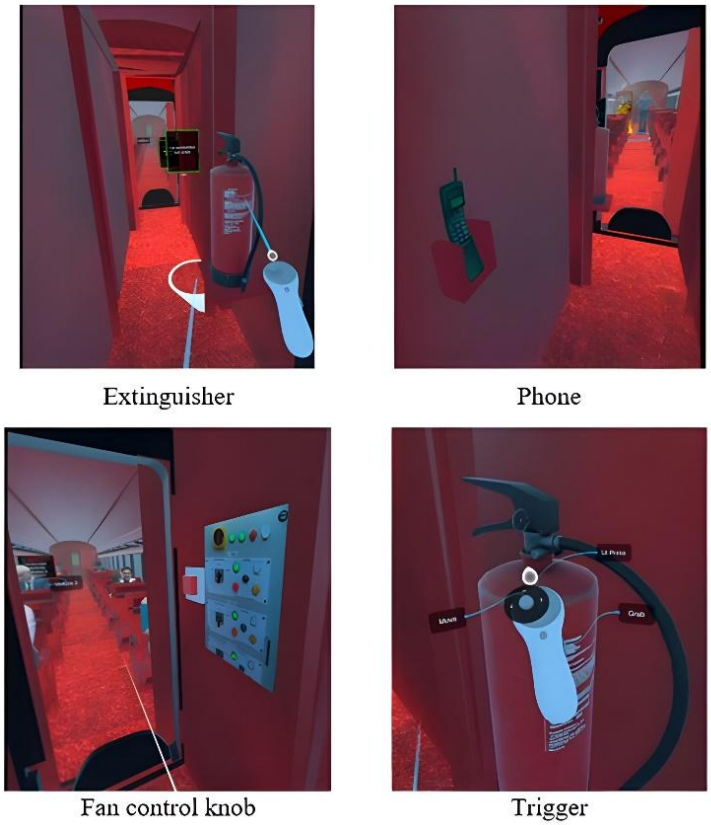


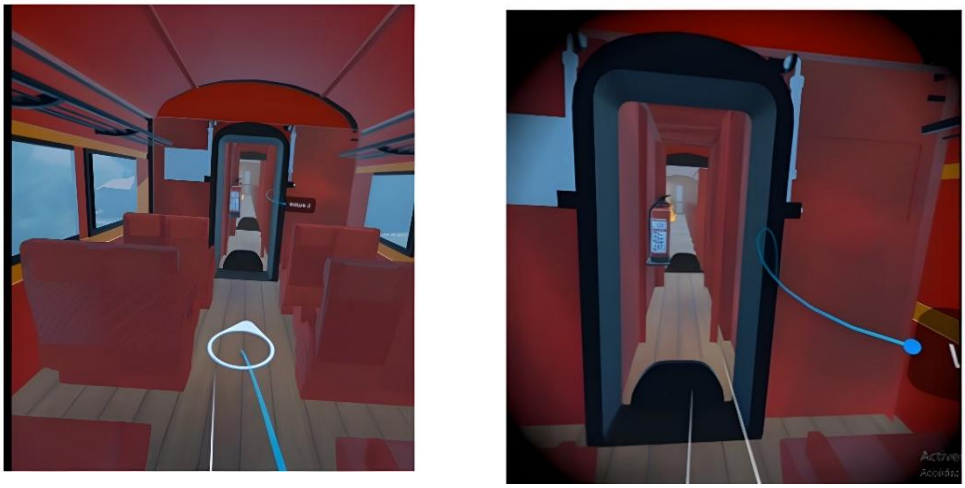
Figure 4. Interactive game object examples

2.3 Technique for navigating within VR environments

In Virtual Reality (VR) applications, moving around the virtual world is one of the basic actions. According to [26], two distinct methods facilitate movement within virtual

environments: teleportation-based locomotion and continuous locomotion. Teleportation locomotion involves the immediate relocation of the user's position. In contrast, continuous locomotion mimics walking, allowing the user to move gradually in the intended direction. Each of these techniques presents its advantages and disadvantages, necessitating thorough consideration during the design of a Virtual Reality Serious Game.

For this study, the chosen navigation techniques were teleportation and continuous locomotion, as shown in Fig. 5. This decision was based on the expectation that teleportation could reduce the occurrence of motion sickness compared to continuous movement. While the latter offers heightened immersion, it is also known for its potential to induce motion-related discomfort.



(a) (b)

Figure. 5. Illustration of the teleportation technique. (a) Presence of teleportation pointers (White circle) (b) The view experienced by the user.

2.4 Non-player characters

In the context of this serious game, artificial non-player characters (NPCs), as depicted in Fig. 6, were used to represent passengers. This representation was enhanced by an audio clip that accurately replicated the sound of a train.

Figure. 6. Non-player character (NPC) representing a passenger within a VR serious game application.

2.5 Educational Achievements and Narrative Frameworks

This section outlines the design process for an immersive virtual reality (VR) prototype aimed at improving personal fire safety skills within a training context. The approach involves interactive scenarios that guide individuals through emergency procedures. The acquisition of knowledge and practical skills occurs in two stages:

- Initial Phase: During this stage, individuals become acquainted with safety regulations. They gain an understanding of procedural steps and their sequence through textual messages and animations.
- Advanced Stage: In this phase, acquired knowledge is reinforced. Individuals actively practice executing emergency procedures through practical exercises.

Each railway operator may have specific Standard Operating Procedures (SOPs) for handling fire incidents. Personnel should be aware of these protocols and adhere to them scrupulously. Railway operators recognize the critical importance of having well-defined procedures in place to address fire emergencies swiftly and effectively. These Standard Operating Procedures (SOPs) serve as a crucial guide for railway staff, ensuring a coordinated and efficient response.

The objectives of the game are derived from these SOPs, which provide a series of learning objectives to be taken into account when designing a training program for conductors to enhance fire safety in rolling stock. The standard procedure described above highlights the following steps and actions:

- Immediate Action:

First Response: When a fire is detected, staff should act promptly. This includes locating the fire source and alerting the driver, as shown in Figure. 7.

Figure. 7. The player discovers the fire and alerts the driver.

- Isolation and Containment:

✓ Limiting Spread: The player isolates affected areas by closing doors and cutting power, as shown in Fig. 8.

✓ Preventing Panic: The player calmly guides passengers away from the fire zone as shown in Fig. 9.

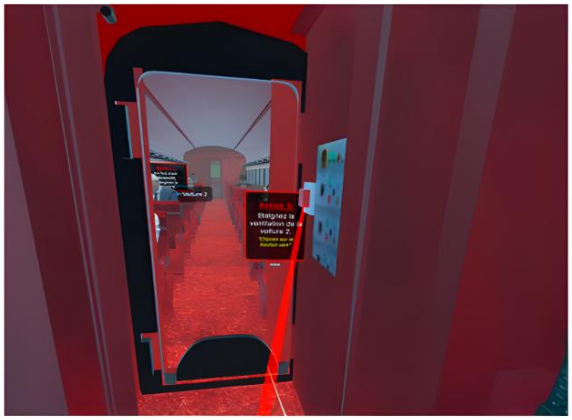


Figure. 8. The player turns down the air conditioning on the train.

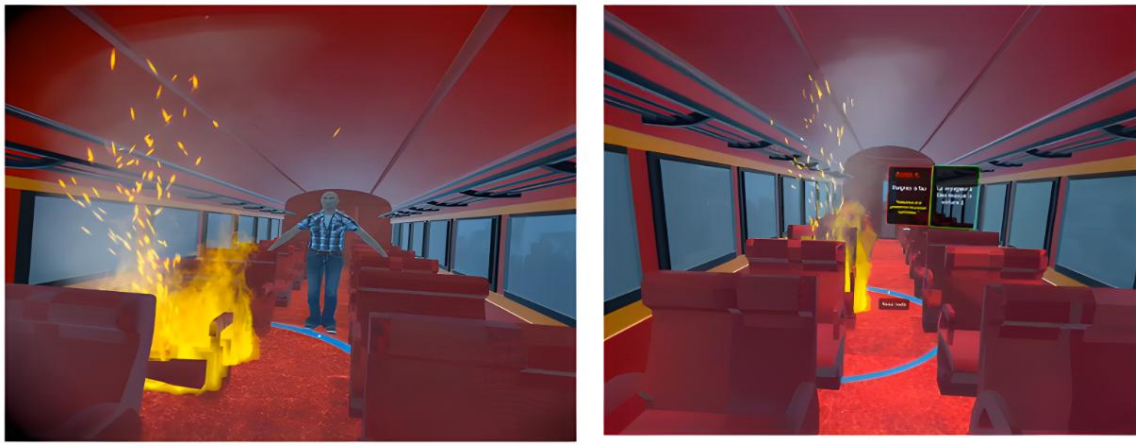


Figure. 9 The player evacuates all passengers to another coach "no fire"

- Fire Suppression Techniques:

✓ Fire Extinguishers: Staff should understand the types of fire extinguishers available on board and how to use them effectively, as shown in Fig. 10.

Figure. 10 The player looks for the fire extinguisher and put out the flames.

The virtual reality serious game developed in this research has been structured to operate independently, eliminating the necessity for external assistance during gameplay, as shown in Fig. 11. The interactions between the game and the player have been intentionally kept straightforward, transparent, and easy to carry out. This is facilitated by:

✓ The pedagogical approach used to dispense fire safety knowledge. This method provides instructions before responding to the event. In other words, trainees were told what to do before responding to the event to learn appropriate behavior.

✓ The prompt feedback that demonstrates the outcomes of the trainees' actions.

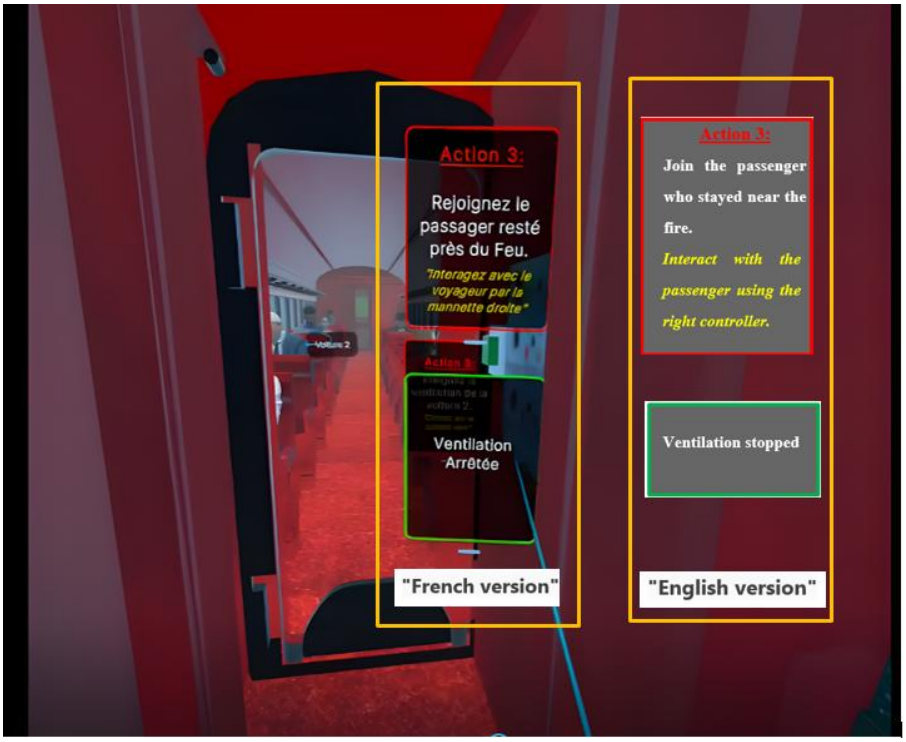


Figure. 11 Pedagogical approach (Action in red color and response in green color)

3 Analysis

3.1 Collecting data and participants

In order to assess the VR Serious Game prototype's effectiveness, a user-centered laboratory experiment with thirty volunteers was conducted. Participants were recruited from a game arcade, encompassing both gamers and their families, to ensure a diverse sample for the study. The experimental process commenced with participants reviewing a comprehensive information sheet outlining the study's objectives and content. Subsequently, they provided informed consent by signing a form, authorizing the research team to store and utilize the collected data for research purposes. Two questionnaires were sent as part of the data collection procedure. The initial questionnaire was distributed before the VR training, while the subsequent one followed the training session.

Before the simulation began, participants received training on how to use the VR navigation system and instructions on how to use the VR equipment.

A total of thirty participants (5 females and 25 males) were involved in the study, with ages ranging from 20 to 58; however, over 80% fell within the 20 to 25 age group. Furthermore, 12 participants (30%) had no prior exposure to virtual gaming, whereas the majority of participants (70%) claimed previous experience with VR games. Regarding fire safety training, ten participants reported having some form of training (33%), while the remaining 20 participants had little to no fire safety training (67%).

3.2 Evaluation

After the development of the prototype system, a series of studies and trials were conducted to confirm its suitability for two specific purposes: fire safety training on board passenger trains and recovery process training. An evaluation framework was established, consisting

of three key components: (1) interface assessment, (2) emotions assessment, and (3) performance evaluation.

The interface assessment focused on evaluating the realism of the virtual environment and game navigability and interactivity. In terms of realism, the majority of participants (87%) indicated that the VR fire simulation felt realistic. However, some participants (13%) felt that the absence of haptic feedback when manipulating objects rendered the interaction unrealistic. Concerning game navigability and interactivity, a majority (75%) reported that it was intuitive, interactive, easy to use, and easy to learn. However, a small percentage (7%) complained about difficulties controlling the character even with VR controllers, citing issues such as trouble moving to the desired location, pressing the wrong button, and being unable to select items.

The user-experience survey, administered to participants, solicited descriptions of their emotions. Participants were asked to rank how comfortable they felt during the experience on a scale of 1–5, with 5 indicating very comfortable. Subsequently, the survey inquired about participants' levels of fright in the game on a scale from 1 to 5, with 5 indicating the highest degree of fear. Finally, participants were asked to rate how engaged they felt in the game on a scale from 1 to 5, with 5 indicating the highest degree of engagement. Fig. 12 depicts distributions for participants' responses to these survey questions, providing valuable insights into the emotional aspects of their interaction with the prototype system.

According to the results of the participants' emotions assessment, a significant portion reported feeling more comfortable (40%) and engaged (57%) during the VR experience. However, a few participants (6%) mentioned that the fire simulation induced feelings of fright at times. Additionally, there were responses (10%) indicating that some participants felt dizzy or experienced motion sickness while using the VR application.

To strengthen the validity of these findings, inferential statistical analyses were conducted. Independent samples t-tests revealed that participants with prior VR experience reported significantly higher comfort ($p < 0.001$) and engagement ($p < 0.001$), and significantly lower fear ($p < 0.001$) compared to those without VR experience. In contrast, no statistically significant differences were found between participants with and without prior fire safety training across any of the emotional dimensions (comfort, fear, or engagement).

The differences between age groups were examined using a one-way ANOVA. Results showed significant differences in comfort ($p = 0.001$) and fear ($p = 0.009$), indicating that age may influence emotional responses to the VR simulation. On the other hand, engagement showed little variation ($p = 0.658$). Pearson correlation analyses between age and emotional scores revealed no significant linear relationships.

Finally, performance evaluation focused on knowledge transmission. A large majority (80%) of participants stated that the simulator provided clear and valuable recommendations that enhanced their understanding. Many also reported a loss of time awareness during the experience, suggesting a high level of immersion, which is known to positively impact memory retention in virtual learning environments.

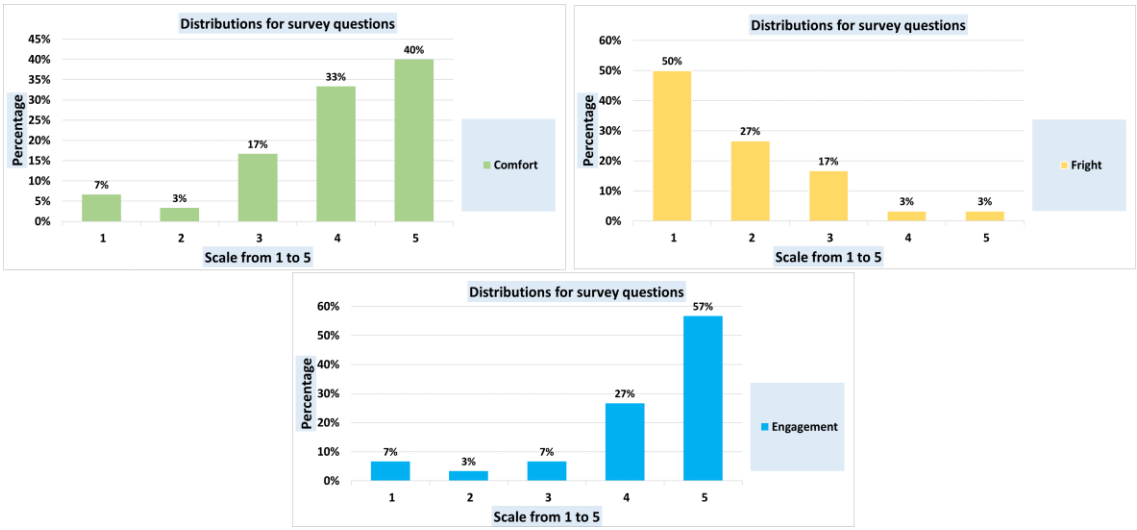


Figure. 12 Distributions for survey questions

4 Discussions

This research paper presents the development of a simulation tool for training railway personnel to respond to rolling stock fires. The approach incorporates serious gaming concepts and immersive virtual reality (VR) technology to achieve simulation objectives. By utilizing immersive VR serious games, individuals can be effectively taught and trained to perform critical actions and tasks required during emergencies while ensuring their safety and not posing any threat to the environment.

This simulation tool provides a guided process enabling the trainee to systematically acquire knowledge of fire procedures, following a step-by-step approach tailored to various fire outbreak scenarios. Ultimately, the trainee faces a spontaneous fire ignition challenge. In this scenario, the fire may ignite anywhere within the train, and it becomes the trainee's responsibility to execute the procedure correctly in the prescribed sequence.

The instructional content seeks to offer an alternative training method for instructing safety protocols and practicing emergency procedures. The objective is to supplement theoretical training by enabling trainees to engage in practical scenarios and experiment with different situations.

The feedback from participants highlighted both the strengths and areas for improvement of the VR prototype. Many participants appreciated the realistic nature of the VR fire simulation, although some suggested that adding haptic feedback could enhance the experience. The majority found the game intuitive and user-friendly, though a few faced challenges with character control. Emotionally, participants generally felt comfortable and engaged during the VR experience, with some noting occasional feelings of fright or motion sickness. Importantly, most participants felt that the simulator provided clear and valuable recommendations, significantly enhancing their understanding of fire safety procedures. These insights underscore the effectiveness of the VR approach in delivering realistic and engaging training, while also identifying potential enhancements to further improve the user experience.

The results indicate that the VR prototype had a substantial impact on enhancing the knowledge of the participants who evaluated the training solution. Additionally, the outcomes demonstrate that the developed prototype successfully meets the pedagogical objectives of safety training by delivering clear and valuable recommendations.

Moreover, rail companies have traditionally used full-scale tests to train their personnel for emergencies. However, these tests have several significant drawbacks. Firstly, the results often lack realism because the scenarios are controlled and predictable. Secondly, conducting full-scale tests is expensive, requiring substantial financial resources for setup, execution, and maintenance. Additionally, these tests pose logistical challenges, including the need for extensive coordination and the potential disruption of regular railway operations. Consequently, this prototype holds the potential to revolutionize traditional hands-on training methods. Beyond simulating virtual emergencies under adverse conditions, this training can be conducted at various times throughout the year without disrupting regular railway operations.

Immersive VR technology effectively addresses these limitations. By creating a highly realistic and interactive virtual environment, VR training can simulate a wide range of emergency scenarios without the associated safety risks. This allows trainees to practice and refine their responses in a safe and controlled setting.

In conclusion, integrating immersive VR into railway safety training offers a superior alternative to traditional methods. It enhances realism, reduces costs, and overcomes logistical barriers. This innovative approach not only improves the effectiveness of training but also ensures the safety and preparedness of railway personnel. The results of this study demonstrate that the VR prototype meets the initial research objectives by providing an effective and engaging training solution.

The potential impact on the industry is significant, as this technology can be scaled and integrated with existing training systems. By adopting VR training, railway companies can enhance their training programs, making them more efficient and accessible. The scalability of VR technology allows for widespread implementation across various training scenarios, ensuring that personnel are well-prepared for emergencies. This approach can be adapted to other industries as well, offering a versatile and effective training solution for a wide range of applications.

5 Conclusion

Although the designed serious game has the potential to transform traditional training methods, it is still in its pilot phase. Future efforts will involve conducting a case study with railway workers to evaluate the feasibility and effectiveness of this prototype in fire safety training for rolling stock. By including real end users, the evaluation will be more representative of actual operating situations, increasing the training system's ecological validity.

Additionally, we plan to implement interactions between users and virtual characters, enabling users to assist in passenger train evacuations or coordinate with other personnel during fire safety scenarios. This research significantly advances the fields of virtual reality, serious gaming, and safety training by integrating immersive VR technology with serious gaming concepts. Our findings demonstrate VR's potential to improve knowledge retention and practical skills. Furthermore, the development of a user-centered evaluation framework contributes to methodological advancements in assessing VR training effectiveness.

Future development will focus on broadening the scope and scalability of the VR training system. This includes incorporating advanced haptic feedback to enhance interaction realism and address issues related to motion sickness. We also plan to adapt the system for multi-user scenarios, facilitating collaborative training sessions that reflect real-life emergency responses. Another direction involves leveraging artificial intelligence to create adaptive training modules tailored to individual needs and performance. Finally, exploring the integration of this VR training system with existing training programs will be crucial to ensure seamless adoption and maximize its impact on the industry.

Conflicts of Interest

The authors declare no conflict of interest.

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