COMPARATIVE STUDY FOR TRAINING USING VIRTUAL REALITY SIMULATING AND CONVENTIONAL FIREFIGHTING

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1. **Abstract:** Ports are critical hubs for global trade, and the complex environments they encompass present unique fire hazards due to the presence of flammable materials, large machinery, and congested spaces. Effective firefighting preparedness among port workers is essential to ensure rapid response to emergencies and minimize damage. Traditional firefighting training methods, while valuable, often come with limitations such as safety concerns, high costs, and limited scenario variety.

The fire safety skills training content is too large and complex, due to many problems in the actual training which requires varies and integrated training techniques such as simulation training systems. Virtual seaport firefighting training system based on virtual reality (VR) which plays is an important role in building capacities and enhancing port-workers skills .

This study investigates the impact of virtual reality (VR) firefighting simulations on enhancing the firefighting capabilities of port workers. VR technology provides an immersive, risk-free environment where workers can experience realistic fire scenarios tailored to the specific challenges of port environments. These simulations offer dynamic training modules that replicate various fire hazards—such as fuel spills, container fires, and shipboard emergencies—allowing port workers to practice their response strategies, decision-making, and teamwork under pressure. The research examines how VR simulations improve key firefighting skills such as hazard recognition, risk assessment, and the effective use of firefighting equipment. By providing frequent and varied training opportunities without the logistical challenges of traditional methods, VR simulations have shown to significantly enhance port workers' readiness for emergency situations. Additionally, the study highlights the benefits of cost efficiency, safety, and scalability of VR-based training.

The findings demonstrate that VR firefighting simulations are a powerful tool for improving the firefighting preparedness of port workers, equipping them with the necessary skills to handle high-risk situations more effectively, thereby contributing to a safer port environment.

Furthermore the study provides a case study represented in an effective platform for firefighting training system in ports , as well as a comparative study between firefighting training using VR Simulation Techniques and Hands-on Training for Port Community is proposed in this research.

2. Introduction:

It is frequently stated that the most frequent source of significant losses in terms of both life and property is fire disasters. It can occur at any time and anywhere. Remarkably, the majority of people lack the necessary skills to handle a fire when it occurs. People frequently panic and are unsure of how to escape from a fire incident or put out the flames.
There have been numerous documented fire incidents during the past five years that have had catastrophic results, including the loss of life, property, or equipment. For instance, one of the worst harbor accidents in history occurred in Beirut, which nearly devastated the port and claimed a significant number of lives and damaged a lot of equipment.
It is acknowledged that human mistake, whether in prevention techniques or in a lack of firefighting skills and knowledge, accounts for 80% of fire incidents (Vladimir et al., 2022). This calls for increasing capacity by eschewing conventional training techniques and switching to more cutting-edge technologies.
The virtual reality-based virtual firefighting training system may be useful for providing instruction in real time.
With the use of virtual reality training technologies, students can experience a variety of training scenarios in a single session. Depending on the firefighter's duty category and the incident being trained for, several environments are used for training. Training of communication and coordination skills is necessary in the simulation environment of a fire on ships and in ports (Tao et al., 2017). The complexity of the training can vary greatly, ranging from the training of relatively fine motor skills for specific equipment to large scale live training operations. It is very costly and challenging to train skills that are only applicable in very complex settings. For instance, learning how to effectively communicate between various emergency response services in crisis situations (Molka-Danielsen et al., 2018) or repeatedly practicing fire evacuation procedures (Sharma et al., 2017) would be extremely difficult and costly to coordinate in real life due to the significant amount of personnel and equipment required for these scenarios. It is also simple to train several staff categories in a single, cohesive scenario by having control over what is being taught in a virtual reality simulation for each trainee separately. This eliminates the need to deplete the department's human resources for every area of training. During training, specific aspects of a scenario can be replicated precisely to enhance targeted skill sets. The ability to gather data during a highly standardized training process allows for the accurate identification of trainee weaknesses and provides immediate feedback for improvement. In the coming years, this approach will become the standard for training. If technological advancements are not the driving force, then the business benefits and cost savings will undoubtedly take the lead.

3. Literature Review:

Firefighting is a physically demanding profession that requires specialized training to ensure the safety, performance, and overall well-being of firefighters. Recent literature has explored various aspects of firefighting training, ranging from skill development to the physiological effects of training programs. This literature review will examine the key findings from recent studies on the effectiveness of firefighting training and its impact on firefighters' safety, health, and performance.
Firefighters must develop critical skills in hazardous environments, which can be difficult to replicate in real-world training scenarios. To address this, Clifford et al. (2018) explored the use of virtual reality (VR) systems in firefighting training, specifically for wildfire suppression. The study found that different display systems in VR impacted the level of situation awareness (SA), a

critical skill for firefighting, with head-mounted displays providing better immersion and portability compared to high-definition TV displays. This suggests that integrating advanced VR technologies can significantly enhance training by creating realistic simulations without the risks associated with live training exercises.

On the physical health side, firefighting training programs have shown significant benefits in improving firefighters' fitness. A study by Lan et al. (2020) followed firefighter recruits through fire academy training and into their probationary period. The results indicated improvements in fitness metrics, such as reduced body fat percentage and increased physical endurance. However, these improvements diminished after graduation, highlighting the need for continuous physical activity post-training. Another critical finding was the increase in blood pressure during training, which persisted into the probationary period, suggesting that while training enhances fitness, it may also introduce cardiovascular risks that need to be addressed.

Additionally, several recent studies have focused on improving firefighter safety gear through innovative materials. For instance, He et al. (2022) developed a self-powered fire alarm e-textile that could be integrated into firefighting clothing. This technology allowed for early detection of clothing damage caused by excessive heat, enhancing both safety and rescue operations. Such innovations in personal protective equipment (PPE) could further reduce the risks faced by firefighters in extreme conditions.

Furthermore, the role of environmental and chemical safety in training grounds has been scrutinized. Thai et al. (2022) examined the release of harmful alkyl substances (PFAS) from concrete in firefighting training grounds, particularly under simulated rainfall conditions. This study highlights the environmental impact of firefighting training and the potential health risks associated with chemical exposure during training exercises.

4. Problem Statement

The unique environment of ports poses significant firefighting challenges, including large-scale fuel storage, flammable cargo, chemical spills, and restricted access to fire hazards on ships or docks. Current firefighting training programs may not fully address the specific risks and complexities associated with port environments, leading to potential gaps in emergency response capabilities. Additionally, coordination between different emergency response teams—such as maritime, port authority, and local firefighting units—can be limited, resulting in delays or inefficiencies during critical incidents.

Capacity Building system for firefighting skills is extensive and complex due to many challenges facing practical training such as:

- High costs of Training equipment
- Training Restrictions specially Places that has the highest priority of national security Such as ports
- The inability to provide multiple different realistic scenarios without risk factor

5. Objectives

Recently, many fire accidents have been recorded in seaports, and they have caused severe losses in lives and equipment, in addition to large financial losses that took a lot of time to be compensated and despite the presence of distinguished hands-on training in most of the ports, this training faces difficulties in providing the appropriate environment. In addition to creating scenarios that 100% simulate reality, accordingly.

Through this study we propose an effective platform firefighting training system in maritime based on virtual reality applications. Also, A Comparative Study between Fire Fighting training using VR Simulation Techniques and Hands-on Training for port in order to create a balanced environment that simulates the reality of firefighting training and meets all the needs of hands-on training in the most difficult conditions and hazards to ensure sustainability.

The research aims to direct the maritime transport sector and ports to head towards the training process in firefighting using virtual reality simulations and the flexibility it includes in the presence of possible scenarios that the firefighting crew may be exposed to in ports and with a great opportunity to reduce the risks of training to zero.

The research aims to demonstrate modern training methods in order to raise training awareness for the usage of innovative applications in the maritime transport sector, such as the virtual reality techniques in fighting fire, through comparative study between applied training and virtual reality training technique.

The research study aims create a general trend to implement the research concept and methodology not only in Egyptian ports, but expand the implementation area in the future on various maritime transport bodies globally and internationally in order to ensure great opportunities for sustainability.

The research aims to highlight the advantages of VR firefighting training such as: flexibility, diversity of training techniques, and its coverage of various disciplines, including firefighting crews in particular, and safety and security crews in the port community in general, in addition to the most important element, which is training cost reduction, the matter that allows involving more of port workers and maritime transport sector than the traditional hands-on training techniques.

The research study aims to popularize training innovations in various fields, especially combating fire accidents through implementation in some Egyptian ports, container terminals, and shipping companies

6. Research Design

The research is concerned with studying a real-time comparison between firefighting training with traditional methods such as hands-on training and innovative methods such as VR Simulation, with an assessment and analysis of the results and outcomes in both cases, as a result a comparative study will be obtained to determine the impact of firefighting VR simulation training, recommendations and outcomes [Fig. 1].

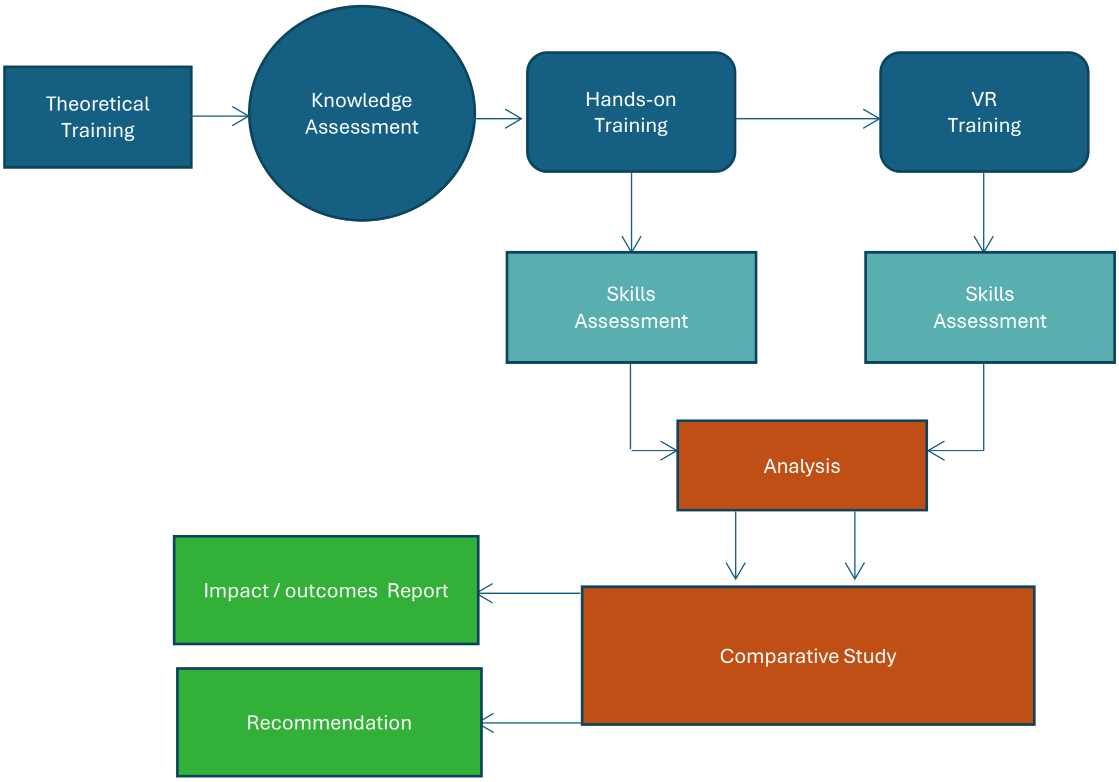

Fig1. Research Phases

The research concept is divided into the following main phases as shown in Fig1

Courses establishment and training materials

This work package either establishes new scientific materials for firefighting or develops programs that Port Training Institute training materials already provides. In addition to:

- Establishment of practical training scenarios, Hands-on Training, and VR simulation training.
- Preparation of exams and trainees assessments before and after training using both techniques (hands-on, VR).

- Reviewing the training materials to cope with and fulfil the modern trends of IMO, ILO for safety and security, as well as OSHA standards.

VR simulation and Equipment installation

This work package is specialized in determining and following up the technical specifications of the simulation system for fighting fire with virtual reality technology, as well as, the installation of the training operating system and applications.

- The Installation of software and application used in comparative studies such as analysis of the assessment results.
- Also, the development of port equipment scenarios in terms of fire accidents during cargo handling.

Research Implementation

This work package implements:

- Theoretical training for trainees
- Operational and hands on training
- VR training
- Assessment of trainees' knowledge, skills and attitude.

Comparative study, assessments analyses, and outcomes analyses

- Establishment of an assessment criteria to be a platform for the research outcomes analyses.
- Establishment A Comparative Study between Fire Fighting training using VR Simulation Techniques and Hands-on Training for Port in order to create a balanced environment that simulates the reality of firefighting training and meets all the needs of hands-on training in the most difficult conditions and hazards to ensure sustainability.

7. Methodology

An experimental design was employed, involving two groups: one group received VR-based firefighting simulation training (experimental group), while the other group received traditional firefighting training (control group). Pre- and post-training assessments were conducted to evaluate Accuracy of risk response, critical skills, and level of situation awareness.

The participants in this study were students enrolled in a variety of academic programs at a training institute, all of whom had no prior experience or specialized knowledge in firefighting. The sample consisted of students from diverse fields, including Engineering, Business, Information Technology, Health Sciences, Arts and Humanities, and Social Sciences. Given that these students are unfamiliar with firefighting and safety protocols, they provide a unique opportunity to evaluate the effectiveness of VR-based firefighting training as compared to traditional training methods. By selecting students from various academic disciplines, the study ensures that the findings will be applicable to a wide demographic, thus enhancing the generalizability of VR training for emergency response scenarios.

A total of 60 students were selected for the study, with 30 students in each group. Participants were randomly assigned to either the experimental or control group, ensuring an unbiased distribution. where the criteria for selected participants were from 25-40 years and they have no a prior firefighting experience or emergency response training.

Both groups took a Pre-training Assessment to measure their Accuracy of risk response, critical skills, and level of situation awareness. **The Accuracy of Risk Response** refers to how well firefighting teams and emergency responders assess, react to, and manage the risks involved in fire situations. This includes the identification of potential hazards (e.g., structural integrity, hazardous materials, weather conditions), evaluating the likelihood and potential severity of those risks, and implementing an appropriate response to control or mitigate those risks.
The accuracy of risk responses in firefighting involves ensuring that the actions taken—such as evacuations, suppression tactics, and resource allocation—are appropriate for the specific situation. This includes choosing the correct firefighting techniques (e.g., direct attack, indirect attack), protecting first responders, and considering environmental conditions to minimize harm and maximize safety for both responders and the public. (IFSTA, 2017).
The Critical Skills are defined as a set of essential skills required to perform tasks effectively, especially in complex or high-risk situations. The Critical Skills is focusing on developing practical competencies and readiness, enhancing speed and efficiency in response, decision-making, and communication. (Smith, 2019).
The Level of Situation Awareness is the ability to perceive environmental elements within a fire ground, comprehend their meaning in real-time, and predict their status in the near future to make informed decisions and ensure safety (Endsley, 1995).

The Experimental Group of participants received VR-based firefighting training. The VR simulation created realistic fire emergency scenarios, allowing students to practice various firefighting strategies, hazard assessments, and decision-making processes. They engaged in several VR sessions to develop their skills in a safe, controlled environment.

While the Control Group received traditional training that includes theoretical lessons on firefighting protocols and hands-on practical drills using firefighting equipment in a controlled setting. Both groups received 10 hours of training, spread over a period of two weeks, with each session lasting 1-2 hours. The total training time will be the same for both groups to control for training duration.
After completing the training, both groups completed a post-training assessment identical to the pre-training one. This allowed for direct comparisons of Accuracy of risk response, critical skills, and level of situation awareness between the two groups.

The result

This section presents the statistical analysis conducted on the pre-test and post-test data from both the experimental and control groups.

The objective of the next analysis is to assess whether there are significant differences in the participants' performance across three key measures: Accuracy of risk response, critical skills, and level of situation awareness. The table below summarizes the descriptive statistics for all variables collected, providing an overview of the participants' scores before and after the training for both groups.

Table-1. Descriptive Statistics

Measure	Group	Mean Score	Standard Deviation (SD)
Critical Skills	Experimental	30.3	2.2
	Control	31.2	2.1
Accuracy of Risk Response (%)	Experimental	86.2	2.7
	Control	85.7	2.8
level of situation awareness (%)	Experimental	91.1	2.1
	Control	90.5	2.3

In the **Critical Skills** measure, the **experimental group** had an average of **30.3 seconds** (SD = **2.2**), while the **control group** had an average of **31.2 seconds** (SD = **2.1**). This shows a slight difference between the two groups at the pretest stage. For **A Accuracy of Risk Response**, the **experimental group** had a mean score of **86.2%** (SD = **2.7**), while the **control group** had **85.7%** (SD = **2.8%**). **level of situation awareness** was measured at **91.1%** (SD = **2.1%**) for the **experimental group**, and **90.5%** (SD = **2.3%**) for the **control group**.
Based on the pre-test results for both the experimental and control group, the analysis indicated that there are no significant differences between the experimental and control groups in the pre-test scores for Accuracy of risk response, critical skills, and level of situation awareness. The means are very close, and the standard deviations are comparable, suggesting that the groups were similar in their initial levels of performance before the training.

To evaluate the effectiveness of the VR training, we employed **paired samples t-tests** to compare pre-test and post-test scores within each group. The following table present the statistics for Experimental group, along with the results of the paired samples t-tests, to highlight the key findings of the analysis.

Table 2. Paired Samples t-test Results for **Experimental** Group

Dimensions	t-value	Degrees of Freedom (df)	p-value
Critical Skills	4.89	29	0.001
Accuracy of Risk Response (%)	2.12	29	0.043
level of situation awareness (%)	2.08	29	0.046

The Paired Samples t-test Results for Experimental Group **has shown a** significant improvement in the capabilities of trainee where the test for **Critical Skills** yields a **t-value of 4.89** with **p = 0.001**, indicating a statistically significant difference ($p < 0.05$). This suggests a significant improvement in the experimental group's critical skills after training. And the test for **Accuracy of Risk Response** gives a **t-value of 2.12** with **p = 0.043**, which is less than 0.05, indicating a statistically significant improvement in accuracy after training. The t-value of **level of situation**

awareness 2.08 and p-value of 0.046 indicate a significant improvement in **level of situation awareness**, meaning the training led to a measurable increase in participants' adherence to safety protocols.

Table 3: Paired Samples t-test Results for **Control** Group

Measure	t-value	Degrees of Freedom (df)	p-value
Critical Skills	**4.45**	**29**	**0.001**
Accuracy of Risk Response (%)	**3.67**	**29**	**0.002**
level of situation awareness (%)	**2.58**	**29**	**0.016**

Table 3. showed The Paired Samples t-test Results for Control Group where the analysis has **also shown** a significant improvement in the capabilities of trainee where the test for **Critical Skills** yields a t-value of 4.45 and the p-value of 0.001 indicate a significant improvement in Critical Skills after the training. And the t-test for **Accuracy of Risk Response** gives t-value of 3.67 and the p-value of 0.002 suggest a significant improvement in tool usage accuracy post-training. While for **level of situation awareness** has the t-value of 2.58 and p-value of 0.016 indicate a significant improvement in level of situation awareness meaning the training led to a measurable increase in participants' adherence to safety protocols.

The paired t-test results indicated that both the experimental and control groups demonstrated significant improvements in performance after receiving training. However, to assess the extent of these improvements within each group and to compare the magnitude of change between the groups, it is crucial to measure the effect size (Cohen's d) . This will allow to determine which training method—VR-based training or traditional training—has a more substantial impact on performance.

Table 4. effect size (Cohen's d) for groups

Measure	Cohen's d (Experimental)	Cohen's d (Control)
Critical Skills	**-2.23**	-1.45
Accuracy of Risk Response (%)	**1.82**	1.36
level of situation awareness (%)	**1.95**	1.52

The **Cohen's d** values in table 4 indicated that the experimental group experienced larger effects compared to the control group, specifically, the experimental group had a larger improvement in **Critical Skills** (**Cohen's d = -2.23**), **Accuracy of Risk Response** (**Cohen's d = 1.82**), and **level of situation awareness** (**Cohen's d = 1.95**), all of which were significantly higher than those of the control group. These findings highlight that VR training not only produced statistically significant improvements but also had a stronger practical impact on the trainees' performance.

To further substantiate the results and determine whether the differences between the groups after the training were statistically significant, we conducted **independent t-tests** on the post-test scores.

Table 5: independent t-test Results

Measure	t-value	Degrees of Freedom (df)	p-value
Critical Skills	-4.36	58	< 0.001
Accuracy of Risk Response (%)	4.84	58	< 0.001
Level of situation awareness (%)	3.31	58	0.002

The **independent t-test** results confirmed that the experimental group outperformed the control group in all three areas: Accuracy of risk response, critical skills, and level of situation awareness. The t-values for **Critical Skills** (**-4.36**, $p < 0.001$), **Accuracy of Risk Response** (**4.84**, $p < 0.001$), and **level of situation awareness** (**3.31**, $p = 0.002$) all indicated significant differences between the two groups, with the experimental group showing more substantial improvements across all dimensions. The negative t-value for Critical Skills further confirms that the experimental group (VR training) demonstrated higher proficiency in critical skills compared to the control group.

8. Conclusion

The combination of **paired t-tests**, **effect size**, and **independent t-tests** allowed us to not only confirm that both training methods were effective but also to demonstrate that the VR-based training method led to significantly larger improvements in all measured areas. Therefore, the analysis supports the hypothesis that VR training is more effective than traditional methods in improving Accuracy of risk response, critical skills, and level of situation awareness.

Research on the use of virtual reality (VR) in firefighting training has shown promising results in improving both the effectiveness and efficiency of training programs through: Enhanced Learning and Skill Development, Safe and Controlled Environment, repeatability and Personalization, Stress and Psychological Preparedness, Real-Time Feedback and Performance Analytics and Training Accessibility and Scalability

Overall, research supports the idea that VR is a highly beneficial tool for firefighter training. It allows for immersive, repeatable, and safe training scenarios that can enhance both technical and psychological preparedness. However, VR should be viewed as a supplement to, rather than a replacement for, traditional live training. The combination of VR and hands-on exercises offers a comprehensive approach to developing the diverse skills required for effective firefighting. Future research should focus on addressing the technological limitations, enhancing sensory feedback, and further exploring how VR can be integrated into existing training programs.

9. Future Work

Larger sample size or a follow-up study with industry professionals for comparative study will be implemented as well as it will include long-term effectiveness studies and integration of VR with augmented reality (AR) for hybrid training.

The software, the results, training methods and materials used for this study will help provide more future training for the trainees at Port Training Institute, Arab Academy for science, technology, and Maritime Transport.
Results of this study could be used as a base for issuing a guideline for firefighting in the Maritime Industry which goes in line with the updated requirements and regulations of the IMO and ILO.
The guidelines resulted from this comparative study will be used to lead the Maritime Transport Sector in Egypt and the Arab Region toward the development of training using more innovative techniques as the Virtual Reality.

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