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Enhancing Firefighter Training With Virtual Reality: Benefits, Challenges, and Technological Integration

Aperfeiçoamento da Formação de Bombeiros Através da Realidade Virtual: Perspetivas Sobre Benefícios, Desafios e Integração Tecnológica

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The use of virtual reality (VR) in firefighter training represents a promising innovation that has the potential to revolutionise traditional training methods by allowing simulations of high-risk scenarios in a controlled and safe environment. This article examines the benefits and challenges of incorporating VR into training programmes, emphasising its advantages in developing practical skills and preparing for complex situations of emergency. The realism offered by VR enables firefighters to immerse themselves in virtual environments, where they can practise manoeuvres and decision-making without the inherent risks of real fires. This enhances safety and allows scenarios to be repeated at minimal additional cost.

However, the implementation of VR in training faces technical and acceptance challenges. Issues such as the high cost of equipment, difficulties in creating fully realistic simulations — particularly in replicating factors like heat and smoke — and resistance from some professionals to adopting new technologies are significant barriers. Additionally, the need for specialised hardware and the potential for physical discomfort, such as nausea, highlight the importance of an adaptation period.

Nevertheless, studies suggest that VR offers significant benefits, including immediate feedback and the ability to customise training to meet individual needs. The successful integration of VR requires a collaborative approach involving fire brigades and technology developers. This collaboration is crucial to tailor the innovation to the specific requirements of emergency training. The potential of VR to enhance firefighter preparedness safely and efficiently points to its increasing application in public safety, underscoring the importance of future research to optimise its use in real emergency scenarios.

Keywords: remote training, virtual reality, simulation, firefighter training

Aperfeiçoamento da Formação de Bombeiros Através da Realidade Virtual: Perspetivas Sobre Benefícios, Desafios e Integração Tecnológica

A utilização da realidade virtual (RV) na formação de bombeiros é uma inovação promissora, com o potencial de transformar métodos de treino tradicionais, ao permitir simulações de cenários de alto risco de forma controlada e segura. Este artigo explora os benefícios e os desafios da integração da RV em programas de formação, destacando as suas vantagens no desenvolvimento de competências práticas e na preparação para situações de emergência complexas. O realismo proporcionado pela RV facilita a imersão dos bombeiros em ambientes virtuais onde podem praticar manobras e tomada de decisões sem os riscos inerentes ao uso de fogo real, aumentando a segurança e permitindo a repetição de cenários sem custos adicionais significativos.

Contudo, a aplicação da RV enfrenta desafios técnicos e de aceitação. Barreiras como o custo elevado de equipamentos, as dificuldades na criação de simulações completamente realistas, especialmente para replicar fatores como o calor e o fumo, e a resistência de alguns profissionais em adotar tecnologias novas são *questões relevantes. Além disso, a necessidade de hardware especializado e a possível ocorrência de desconfortos físicos, como enjoos, indicam a importância de um período de adaptação.*

Ainda assim, estudos indicam que a RV pode oferecer benefícios significativos, como o feedback imediato e a possibilidade de personalização do treino para responder às necessidades individuais. A integração eficaz da RV requer uma abordagem colaborativa entre corporações de bombeiros e de quem desenvolve a tecnologia para adaptar a inovação às especificidades do treino de emergência. O potencial da RV para elevar o nível de preparação dos bombeiros de forma segura e eficiente aponta para uma aplicação crescente dessa tecnologia na área de segurança pública, destacando a importância de investigações futuras para otimizar o seu uso em cenários reais de emergência.

Palavras-chave: *formação à distância, realidade virtual, simulação, formação de bombeiros*

Introduction

The incorporation of new technologies into vocational training and education has transformed traditional practices (Iatsyshyn et al., 2020; Oliver, 2002), introducing methods that enhance training effectiveness and ensure greater safety and efficiency. Among these technologies, virtual reality (VR) stands out as an innovative tool, particularly in firefighter training (Grabowski & Jach, 2021; Narciso et al., 2020). This article examines the integration of VR into emergency training programmes, discussing the benefits, challenges, and potential of this technology in preparing professionals to face dangerous situations.

The relevance of VR in firefighter training lies in its ability to accurately simulate hazardous environments and high-risk scenarios that would be impractical or extremely dangerous to recreate in real-life conditions. By enabling immersion in controlled, detailed experiences, VR not only enhances firefighters' practical and problem-solving skills but also allows for repetitive, intensive training without the risks associated with "conventional" methods.

However, despite significant advances, VR use faces inherent challenges, including technical constraints, implementation costs, and user acceptance. Analysing these factors is essential to understanding the current and future limitations of this technology in the context of emergency training.

This study seeks to present a critical review of the literature on the implementation of VR in emergency contexts, with a particular emphasis on firefighter training. Through an analysis of recent research and case studies, it discusses the advantages and challenges associated with this technology. In addition to highlighting the importance of VR for simulating high-risk scenarios, the review aims to provide a comprehensive overview of VR's impact on enhancing operational skills and safety in training environments. Ultimately, it seeks to contribute meaningfully to the ongoing debate on technological integration in emergency training, identifying areas where future research could further deepen and expand current knowledge.

Evolution of Virtual Reality

The first device enabling an immersive sensory experience was developed in the 1950s. This pioneering system, created by Morton Heilig (Gutierrez, 2023), marked VR's initial steps and incorporated a combination of visual sensors, sounds, vibrations, and scents. In the years that followed, other devices were developed with similar purposes. Among them was Ivan Sutherland's (1968) contribution, a three-dimensional visualisation system worn as a helmet, designed even before the popularisation of the personal computer. This innovation laid the foundation for research into both virtual and augmented reality. The 1980s and 1990s saw further significant developments, including NASA's *VIEW* project (Fisher, 2016), which focused on space exploration through a multisensory workstation for space simulations. Additional milestones included the invention of the DataGlove (Lasko-Harvill et al., 1988), a glove designed to capture hand movements, and the EyePhone (Gigante, 1993) by VPL, a progression of Heilig's original helmet. These innovations set the stage for a series of devices that established interaction within virtual environments.

The evolution of VR continued with notable innovations, including the BOOM (Binocular Omni-Orientation Monitor; Doerner et al., 2022), which provided stereoscopic 3D display. In the domain of immersive projection, key developments included the Powerwall — a screen with stereo audio; the CAVE system (Cave Automatic Virtual Environment; Creagh, 2003), consisting of four screens; and iCONE (Doerner et al., 2022), which utilised semi-circular screens that enhanced possibilities for immersion and interaction. In the late 1990s, augmented reality was propelled by the development of the MARS system (Doerner et al., 2022), a mobile augmented reality system created at Columbia University. This system provided real-time information about campus buildings via GPS and was visualised through a 3D display (glasses). Simultaneously, advances in more robust and sophisticated graphics hardware, led by NVIDIA (e.g., graphics chips; Chamusca et al., 2022), were complemented by significant software advancements (Doerner et al., 2022; Gutierrez, 2023).

Dynamics and Perspectives of Virtual Reality

The VR system integrates both hardware and software to create sensory experiences designed to be as natural and immersive as possible. It enables interaction through input and output devices, which serve as interpreters between human language and machine language. Despite facing several definitional and conceptual challenges (Furht, 2008; Kardong-Edgren et al., 2019; Singh & Carolina, 2017; Steuer, 1992), VR is recognised as a technique that simulates real or virtual environments in three dimensions, engaging the senses in a manner similar to real-world experiences. The essence of VR should be understood more through the human experience it provides than through the technology itself, introducing the concept of "presence" — the feeling of being in an environment, whether real or simulated. This concept highlights the significance of sensory stimuli in creating the illusion of telepresence.

On the other hand, VR can present an alternative world, accessed through interactions with computer-generated images or objects. In this context, as previously mentioned, presence and telepresence are central elements of the experience. Nevertheless, VR has evolved beyond traditional computer graphics, involving the creation of real-time visuals that not only generate three-dimensional content but also enable sensory interactions, such as mapping hand movements to virtual models, among others. This technological advance extends reality into a continuum (see Figure 1), encompassing the real environment, augmented reality (which enhances reality with digital data), augmented virtuality (which integrates real elements into virtual environments), and pure virtual environments, which aim to fully immerse the user in an alternative reality (Doerner et al., 2022; Furht, 2008; Jerald, 2015).

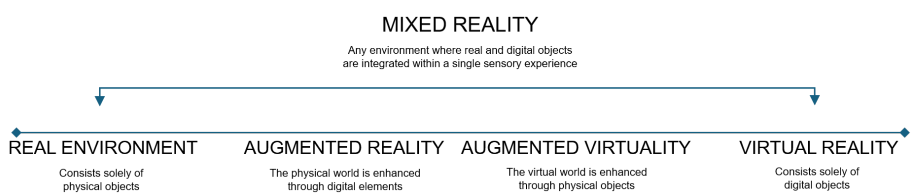

Figure 1: *Virtual continuum*

Mixed reality (MR) represents a significant advancement, particularly in human-computer interaction and the creation of objects that blend real and virtual elements. As such, it challenges human perception and interaction across different realities. However, despite these technological advancements, several challenges and technical limitations remain that can disrupt visualisation within an MR environment. When attempting to combine MR and augmented reality, it becomes clear how important it is to promote an authentic and immersive experience for the user, with interactions that consider both the substance and its context — that is, how these interactions can enhance the authenticity of experiences. For instance, through sound reproduction, a system can recognise that the user is walking in a garden and produce a sound that aligns with the virtual environment. In this regard, interaction functionalities based on sensors that capture pressure and movement play a key role in creating immersive experiences, such as pressure-based interactions on portable devices and movement recognition. Localisation, through technologies such as GPS, Wi-Fi, or Indoor Positioning System (Wahab et al., 2022), is crucial in applications within digital tourism or augmented reality educational games. By integrating with the internet of things, the experience becomes more engaging and enriching, creating new interaction dimensions as the virtual and physical worlds are interconnected, thereby expanding the perception of sensory context (Morris et al., 2020). Advances in technology have driven developments in the field of extended reality, which initially includes VR, augmented reality, augmented virtuality, and MR. The use of extended reality has revolutionised user interaction (e.g., with customers) across various sectors (e.g., tourism), transforming the way destinations are explored and travel experiences enhanced through the integration of virtual and real environments, as well as the convergence of human senses (Blanco-Novoa et al., 2020; Papadopoulos et al., 2021; Santoso et al., 2021).

The Impact of Presence and Narrative on Experience Creation

Presence can be defined as the (apparent) experience of being in a particular place or environment, even if one is located elsewhere in physical reality. In this way, a VR experience is initially shaped by the shift in attention from the physical environment to the virtual one, along with the user's level of engagement, which arises from their response to highly convincing stimuli.

VR is a tool that enables the creation of controlled environments for studying human behaviour (Bourhim & Cherkaoui, 2020), including responses to emotional stimuli such as fear and anxiety. It allows researchers to present sensory stimuli (e.g., visual, auditory) in a controlled and safe manner. This potential can be particularly relevant for research into anxiety disorders, where therapies could be developed to leverage the ability to simulate specific situations that trigger such emotional responses (Woo et al., 2024). On the other hand, the creation of genuine emotional experiences is strongly influenced by the sensation of presence, which is shaped not only by sensory stimuli but also by the coherence of the context and narrative within the virtual environment (in VR, the narrative can be viewed as a structure that not only supports the virtual world but also actively connects the user, making the experience personal and immersive). Thus, the idea that a VR experience is more impactful and engaging when the sensory stimuli are fully aligned with the narrative suggests successful immersion, reflecting the complexity of human interaction with virtual environments, something that could be verified in multiple training contexts. The integration of sensory elements and narrative not only enhances the learner's experience but also improves the effectiveness of the learning process. It is important to highlight that when learners are immersed in realistic and engaging scenarios, both knowledge retention and the practical application of acquired skills are typically improved (Witmer et al., 1996; Witmer & Singer, 1998).

Virtual environments facilitate direct interactions and provide continuous visual feedback, stimulating various senses through human interface devices. They can represent both inaccessible physical spaces and abstract concepts, offering a means to access locations that would otherwise be unreachable. The impact of auditory stimuli in VR highlights the potential of spatial (3D) sound to evoke emotions, such as fear, underscoring the importance of semantic coherence between visual and auditory cues. As such, VR is emerging as a powerful tool for studying human behaviour in controlled environments, particularly, as described above, in the research of anxiety disorders and therapeutic interventions. It allows for the accurate simulation of scenarios that trigger specific emotional reactions, enabling detailed observation of threat perception and the effectiveness of interventions like exposure therapy. This simulation methodology provides unprecedented control over tactile and olfactory stimuli, expanding the possibilities for inducing and studying complex emotional responses in a safe and reproducible environment (Diemer et al., 2015; Suied et al., 2013).

Studies in VR highlight the importance of both bottom-up elements — direct sensory stimuli — and top-down elements — context and narrative — in creating more enriching and emotional experiences. As previously mentioned, presence plays a crucial role in this process, as it significantly impacts the sensation of immersion. The research by Kono et al. (2018) highlights an innovative approach by exploring the potential of VR to intensify emotional experiences, particularly fear and pain. Their system, In-Pulse, combines a solenoid circuit with electrical muscle stimulation, demonstrating that incorporating tactile feedback and physical sensations can significantly enhance immersion and emotional responses in virtual environments. This approach enhances realism and engages the user on a deeper level, provoking intense emotional reactions that simulate real experiences (Diemer et al., 2015; Kono et al., 2018).

The Impact of Virtual Reality in Emergency Scenarios

VR has gained prominence as a promising tool in education and training, providing interactive and immersive three-dimensional experiences that allow users to learn through practice in controlled and safe virtual environments. This technology, which has become more accessible in recent years, enables the simulation (replication) of real situations, offering an alternative to traditional pedagogical approaches, particularly in fields where experiential learning would be impossible or too risky to implement (Bourhim & Cherkaoui, 2020; McGowin et al., 2021; Morris et al., 2020; Papachristos et al., 2017; Woo et al., 2024).

In the emergency field, VR is valuable for simulating complex and hazardous scenarios without the inherent risks, making it essential for training professionals, such as firefighters and emergency teams. VR thus holds significant potential for preparing these professionals to handle high-risk situations, enabling the simulation of scenarios that would be impractical or expensive to recreate in real life. Another advantage of using VR in the emergency field is that it provides safe, customisable training environments, reducing the risks and costs associated with traditional methods. Technological advancements, such as artificial intelligence, enhance the realism and adaptability of virtual environments, making them more immersive and tailored to the specific needs of the users. However, its effectiveness can vary depending on the quality of the hardware and software used, as well as the user's familiarity with the technology. The development of high-quality content, variations in the effectiveness of training, and potential adverse physical effects (e.g., motion sickness) are challenges that must be addressed. Despite the need for specialisation, technological immaturity, and uncertainties regarding the transfer of skills to real-life situations, VR presents an opportunity to enhance training and preparation across various fields, particularly in firefighting (Engelbrecht et al., 2019; Jerald, 2015; Xie et al., 2021).

Challenges and Potential of Virtual Reality in Firefighter Training

Shi et al. (2021) explore the complexities and opportunities of using VR as a training tool for firefighters in search and rescue operations. In this context, VR is presented as an innovative solution that allows the simulation of various realistic and controlled scenarios, replicating situations of emergency. However, the authors highlight one of the main challenges: creating simulations that accurately reflect the conditions faced in real-life emergencies, such as smoke, fire spread, and the sounds of collapsing structures. In this context, all human senses are engaged in the perception and cognition of situations and environments. Any technology that prioritises sight and hearing over other senses (e.g., thermoception, chronoception, touch, smell) will only be recreating an incomplete or partial model and, therefore, not a truly "realistic" one. The real challenge lies in determining whether, even if partial, this model remains valid for the specific purposes being analysed. As such, these simulations must be both detailed and realistic to ensure the user experience closely mirrors reality, enabling firefighters to gain practical experience that is directly applicable to real-life training manoeuvres. Furthermore, the development and upkeep of virtual environments can be both costly and technically demanding.

Another challenge is the adaptation of firefighters to the VR technology itself, as professionals may not be familiar with the devices used in the simulations (e.g., Head-Mounted Display), which can lead to discomfort such as motion sickness (Chang et al., 2020). Therefore, any discomfort experienced when using VR can hinder the effectiveness of the training, making an adaptation period necessary, along with strategies to minimise these adverse effects. Resistance to change is also pointed out as a challenge by the authors, as firefighters are typically accustomed to traditional training methods. Thus, the integration of a VR system into training must be gradual and clearly demonstrate that its practical and theoretical benefits will enhance professional performance, ultimately leading to greater acceptance among firefighters.

Despite these challenges, Shi et al. (2021) also underscore the potential of VR in firefighter training. The authors suggest that the technology enables the creation of a variety of training scenarios that would be dangerous or impossible to replicate in real life. For instance, simulating a fire in a high-rise building or a rescue in collapsed buildings or confined spaces provides a realistic, controlled, and, above all, safe experience for professionals. The ability to create detailed and complex simulations can greatly enhance the readiness of operatives to tackle various types of emergencies, thereby fostering the development of practical skills in a safe environment. Additionally, the capability to monitor and analyse firefighters' performance (e.g. decision-making and responses in stressful situations) enables the identification and correction of specific areas for improvement on an individual basis. Through this type of analysis, training can be personalised and tailored to the particular needs of each firefighter, enhancing both efficiency and safety in real-life operational settings. The ability to repeat various scenarios is also a key advantage of VR, as it enables firefighters to practise exercises repeatedly until they achieve skill consolidation and proficiency while also boosting their confidence. This outcome would be both costly and logistically challenging to replicate in real-life scenarios.

Braun et al. (2022) underline the need for further research to unlock VR's full potential in firefighter training, as there is room to improve VR training effectiveness by developing data-driven guidelines. They highlight the importance of gesture-based communication in multi-participant training scenarios, as well as the challenges of creating high-quality virtual environments that require exceptional graphic quality and visual comfort for a truly immersive experience. In contrast, Zechner et al. (2023) explore VR's application in stress-inducing scenarios, advocating for an incremental training approach that gradually adapts participants to simulated stress. This approach accentuates the value of structuring scenario repetitions in virtual environments to optimise both the learning outcomes and emotional resilience of trainees. Kwon (2021) examines the addition of physical sensations (e.g., heat, wind) to VR experiences, positing that these elements heighten the realism and effectiveness of training by eliciting emotional responses — such as fear and anxiety — that enhance learning without jeopardising participants' safety. This technique could be further refined by incorporating diverse tactile sensations to intensify realism and immersion (Braun et al., 2022; Kwon, 2021; Zechner et al., 2023).

Applications of Virtual Reality in Emergency Training Scenarios: Case Studies

Wheeler et al. (2021) suggest that one of VR's primary advantages in firefighter training lies in its capacity to replicate real-life conditions within a controlled environment, creating high-fidelity scenarios. The immersive quality of such simulations enables trainees to develop both physical and technical skills, enhancing proficiency in using firefighting equipment and adjusting body posture.

The authors highlight that VR promotes more accurate decision-making under pressure, sharpening command skills in emergency contexts. Furthermore, it enhances tactical understanding of firefighting operations and improves team communication and coordination.

In a different study, Bellemans et al. (2020) explored the use of VR within the Belgian Navy to develop a virtual environment for shipboard firefighting. The authors emphasised the creation of highly realistic scenario simulations, allowing firefighters to train under conditions closely resembling real-life situations, yet with significantly reduced physical risks and costs compared to traditional live-fire training. VR's ability to repeat scenarios at no additional cost and indefinitely, along with its minimal environmental impact, stands out as a major advantage in this training context.

Grabowski and Jach (2021) explore VR's potential in firefighter training, particularly in creating complex and hazardous scenarios such as fires in confined spaces. VR allows for intense training without the risks associated with live fire exercises. The use of VR technology ensures the safety of trainees while also enabling the repetition and variation of scenarios that would be impractical or prohibitively expensive to replicate in real life.

Final Considerations

The application of VR technology in firefighter training has been widely recognised for its transformative impact on training methodologies. The studies reviewed highlight the significant advantages of this technology, particularly in terms of safety, simulation realism, and the flexibility it offers in designing training programmes (Bellemans et al., 2020; Grabowski & Jach, 2021; Wheeler et al., 2021). A common conclusion among the authors is that VR enables the recreation of realistic and complex scenarios with controlled levels of risk, scenarios that would be difficult, if not impossible, to replicate in traditional physical training environments. This approach allows for continuous exposure to hazardous situations without compromising the safety of trainees, ultimately leading to better preparation for real-life emergencies.

Furthermore, there is a consensus regarding the financial benefits of using VR, as the ability to repeat scenarios in virtual environments eliminates the high costs and environmental risks associated with physically recreating training situations (Bellemans et al., 2020). The flexibility offered by VR, particularly the ability to modify training scenarios in real-time, is seen as a key factor in enhancing the effectiveness of training programmes. Another point of agreement across the studies is the role of immediate feedback, which significantly contributes to improving firefighters' responses, enhancing their technical skills, and strengthening their decision-making skills under pressure (Wheeler et al., 2021).

Nevertheless, there remains agreement on the challenges and limitations of implementing VR technology. Several authors highlight technical issues, such as the lack of realism in certain aspects of simulations, particularly in recreating physical conditions like smoke and heat, which are essential for firefighting training (Grabowski & Jach, 2021). The high cost of equipment and the need for continuous maintenance are also significant barriers, particularly for fire brigades with limited financial resources (Bellemans et al., 2020). Furthermore, resistance to change and scepticism about the effectiveness of VR as a replacement for traditional training methods continue to be identified as key obstacles to its broader adoption (Grabowski & Jach, 2021).

The use of VR technology in firefighter training marks a significant shift in professional training methods. The studies reviewed demonstrate a consensus on the advantages of VR, focusing on factors such as the realism of the simulations, the safety they ensure, and potentially the financial benefits. Repeatedly recreating physical training scenarios in real life would be financially unfeasible, making virtual environments a valuable alternative. These simulators offer the opportunity to experience a range of scenarios that would be difficult, if not impossible, to replicate safely in real life, allowing firefighters to prepare for emergencies in a more effective and controlled manner.

The primary practical benefit of VR in the context of fire services is its ability to enhance both the safety and efficiency of training. The repetition of scenarios and real-time modification of training conditions offer unmatched flexibility compared to traditional methods while also reducing the costs related to logistics and physical training infrastructure. Another key factor is the inclusion of immediate feedback, which accelerates the learning process and improves decision-making in critical situations. This leads to more comprehensive and accurate training, directly impacting firefighters' ability to respond to emergencies swiftly and effectively.

The widespread adoption of these technologies presents several challenges. Technical constraints, such as the need to reduce hardware and software costs and gain acceptance from professionals, still need to be addressed. While VR costs may be lower than those of real physical simulations, they still pose a significant hurdle to large-scale implementation, particularly in the initial investment phase. Overcoming these challenges will require continued investment in research and development, with the goal of enhancing the quality and realism of simulations, as well as making the technology more accessible and adaptable to the specific needs of fire brigades.

Based on these aspects, it is crucial to devise practical implementation strategies to ensure the efficient integration of VR into training programmes. This could involve establishing partnerships between (technology) companies and fire brigades (municipalities) to create customised solutions that address the operational and budgetary constraints of fire brigades. Moreover, training managers should take a proactive approach to fostering environments that are accepting of VR, encouraging a culture of innovation, and making effective use of technological capabilities.

Finally, ongoing research in this area will be crucial not only for advancing the technical aspects of VR but also for evaluating its long-term impact on firefighter training. Future studies should examine in detail the practical effects of VR in real emergencies, assessing improvements in safety, efficiency, and effectiveness in firefighting and rescue operations. Additionally, it will be important to explore how VR can be integrated alongside traditional training methodologies, creating hybrid programmes that maximise the benefits of both approaches.

In this way, the successful implementation of VR in firefighter training could truly revolutionise the preparation of these professionals, leading to safer and more efficient operations and ultimately contributing to the protection of human lives and property.

Translation: Anabela Delgado

Biographical Notes

Bruno Miguel Pinheiro has served as a firefighter with the Regimento de Sapadores Bombeiros de Lisboa (Lisbon Fire Brigade Regiment) since 2005. He holds a degree in Multimedia Engineering and Computer Science from the Instituto Superior de Tecnologias Avançadas de Lisboa and a postgraduate qualification in Virtual Reality. Pinheiro also completed a master's degree in Computer Science, specialising in Mobile Devices and Multimedia, at the same institution. Currently, he is pursuing a PhD in Digital Media Art through a collaboration between the University of the Algarve and Universidade Aberta.

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