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Video see-through augmented reality fire safety training: A comparison with virtual reality and video training

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ABSTRACT

Safety training is crucial to mitigate the risk of damage when a disaster occurs and can play a vital role in enhancing community response. Augmented Reality (AR) is an emerging technology for safety training that holds great pedagogical potential. This study aims to explore the effectiveness of AR training in terms of knowledge acquisition and retention, as well as self-efficacy enhancement. We developed a new video see-through AR training tool on a tablet to teach users about operating a fire extinguisher to put out a fire following the PASS procedure: Pull, Aim, Squeeze, and Sweep (PASS). The AR training tool was tested with 60 participants. Test results were systematically compared with findings from the literature investigating Virtual Reality (VR) and video-based safety training. The findings indicate that, directly after the training, AR outperformed traditional video training in terms of knowledge retention, long-term self-efficacy, and quality of instructions. However, the AR experience was not as effective as the VR experience in all these areas, but the AR group had a smaller decrease in knowledge over time. These findings suggest that the AR-based training approach offers benefits in long-term memory recall.

1. Introduction

Safety training plays a main role in disaster preparedness for both individuals and organizations (Lovreglio et al., 2021; Jadhav et al., 2023). Its objectives include educating the general public on how to respond to emergencies. Despite improvements in building design, fire hazards are still happening and may occur intentionally or accidentally (Oluwunmi, 2023). The World Fire Statistics show that fires remain a significant threat to public safety while causing devastating damage to lives and property (CTIF_International Association of Fire and Rescue Services, 2022). Building fires are one of the hazards that may be successfully contained by taking appropriate and effective actions in their early stages (Buffington and Ezekoye, 2019; Vairinhos et al., 2021). Correct and timely actions are critical factors in reducing the impact of fire outbreaks. Hence, building occupants should undergo fire safety training for their self-protection. Teaching people how to face fire outbreaks is the responsibility of many organizations, and worldwide regulations in many countries mandate fire safety training. Therefore, special attention must be placed on training individuals on the correct and safe procedural measures. Effective training facilitates the acquisition of knowledge and skills necessary to respond effectively and quickly to fire. A quick response could both save lives and mitigate damage.

Today, most fire safety training programs rely on traditional passive methods, such as classroom-based lectures, videos, and leaflets that may not fully engage participants or effectively simulate real-life scenarios (Rahouti, 2020). The lack of hands-on learning may present challenges regarding information retention over time. These limitations can lead to gaps in training efficacy, with people potentially forgetting crucial information or abilities after some time. Conversely, hands-on firefighting training requires fire permits and significant costs in equipment such as large areas, gas-fed burners, and fire extinguishers (Papakostas et al., 2021). Many innovative solutions have been proposed to overcome these limitations, including computer-assisted approaches, such as Extended Reality (XR).

The fire safety sector is undergoing a digital revolution with the advent of XR technologies encompassing Virtual Reality (VR) and

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Augmented Reality (AR). These technologies have provided new methods for enhancing fire safety training, offering immersive and interactive experiences (Lovreglio et al., 2024). These approaches can closely mimic real-life fire situations in virtual environments, thereby safely increasing engagement and understanding (Caballini et al., 2023). These new training solutions may help users develop proper procedural skills and teach them how to respond once a hazard is detected. XR-based training does not require a real fire. Its use contributes to reducing the carbon emissions that would result from training in real conditions, as well as avoiding any risks and side effects associated with a real fire. To date, VR solutions have been proposed and tested in some studies related to fire safety (Lovreglio et al., 2021; Rahouti et al., 2021; Kang et al., 2023; Ali et al., 2019). However, developing VR-based training solutions is time-consuming and labour-intensive because VR requires modelling the entire virtual world and surroundings to digitally replicate the user environment. Moreover, VR simulations remove the user's perception and awareness from the real world. In a VR environment, users are no longer aware of their physical surroundings as they are immersed in a virtual world that conceals reality. This lack of reality in the digital training scenario may jeopardize their performance in real-life situations.

The use of AR in safety training has the potential to overcome some of the limitations of VR in the field (Kang et al., 2023; Ping et al., 2019). AR solutions remove the need to model the whole surrounding as they blend digital content with the physical environment instead of replacing it (Chong et al., 2009; Höllerer and Feiner, 2024). Users remain physically involved in the real world and see their surroundings with the added extra computer-generated layer of virtual elements (such as 3D models, sound, and text) (Hussien et al., 2020). Additionally, AR training does not require consumables such as fire extinguishers and burners, reducing preparation time and cost (Papakostas et al., 2021).

Different types of devices can deliver an AR experience, such as helmets or smartphones. Many AR applications for disaster preparation have been developed in such a way that digital content is visualized through two methods: Video-See-Through (VST) and Optical See-Through (OST). Typically, VST devices are mobile handheld gadgets, such as tablets, which display augmented surroundings through their camera. In contrast, OST devices are head-mounted wearable displays such as smart glasses and smart headsets that directly present an augmented environment through their transparent visors (Birlo et al., 2022; Lovreglio and Kinateder, 2020; Lovreglio et al., 2024). Given that AR can display digital content embedded in the surroundings in real-time, AR can assist users in performing procedural tasks and serve as an effective training tool whenever needed (Paes et al., 2024; Macchiarella and Vincenzi, 2004; Morra et al., 2020). It allows users to experience the intensity of emergencies, make prompt decisions, and practice prevention procedures in a controlled and real-world environment (Paes et al., 2024). Given its promising benefits, more research is needed to assess AR's effectiveness in the fire safety field.

Researchers have investigated the benefits and challenges of using AR methods across various disciplines (Chiang et al., 2022; Lovreglio and Kinateder, 2020). For fire safety training, the use of AR is quite rare, with just a few applications developed and tested (Kang et al., 2023; Papakostas et al., 2021; Somerkoski et al., 2020; Vairinhos et al., 2021). As AR technology continues to evolve and provide innovative ways to blend digital information with the physical world, it is fundamental to investigate the basic principles and mechanisms to ensure AR training is delivered in an effective, user-friendly, and value-added way. Testing new solutions is critical to understanding how users interact with AR in different scenarios and identifying possible human–computer interaction issues. Without rigorous testing, the potential of AR to improve training outcomes could be unclear. Additionally, empirical evaluation provides researchers with insights into user behaviours, preferences, and potential barriers to adoption, allowing them to fine-tune AR solutions to meet specific public needs and expectations. However, there is limited research available demonstrating the effectiveness of AR-based safety training and comparing AR safety training with other training solutions (Gong et al., 2024). Therefore, there is a need for new research to evaluate the short- and long-term effects of AR safety training for fire emergency management, comparing this new generation of training with traditional and VR training methods.

This study aims to develop and evaluate the effectiveness of a VST AR system for training the public. To achieve this purpose, we developed a new VST AR prototype that can train users on how to operate a fire extinguisher to put out a workspace or domestic fire following the PASS procedure: Pull, Aim, Squeeze, and Sweep (PASS). This new training tool was tested to assess its impact based on user performance. This assessment was undertaken by focusing on knowledge acquisition and retention, self-efficacy, and the quality of instructions. These self-report metrics were selected to compare the collected data with the findings by Lovreglio et al. (2021), who compared the effectiveness of VR and video training. Additionally, the study assessed participants' perceived task load, usefulness, and usability of the training tool to identify potential areas for improvement.

2. Background

Multiple studies related to AR solutions for safety training have been reported in the literature, showing the educational value of AR technology. AR systems have been explored in various safety domains, including the naval industry (Simões-Marques et al., 2019), medical surgery (Wang et al., 2017), aviation (Arjoni et al., 2023), agricultural maintenance (Caria et al., 2019), and CBRN-e (Chemical, Biological, Radioactive, Nuclear, and explosive) attacks (Altan et al., 2022). A comprehensive review of AR applications for safety education was conducted by Chiang et al. (2022), showing the wide use of AR. In the fire safety field, very few applications have been proposed and assessed in the literature for training. They are discussed in this section.

Vairinhos et al. (2021) proposed an AR simulator to train users to recognize the fire hazard type in any office space and respond appropriately during fire emergencies. Preliminary tests indicated that the interaction with the hybrid environment was effective, with positive results in system response. Similarly, Paes et al. (2024) developed and investigated the effect of an OST AR fire safety training system for building occupants compared to conventional video-based training. This study considered the two methodologies in terms of knowledge acquisition and retention, self-efficacy, and intrinsic motivation, and involved 25 participants for each experimental group. The results showed that the AR group outperformed the video group in three key areas: staying motivated, feeling confident in their abilities, and remembering what they have learned. Moreover, the AR training tool was found to be easy to use and more engaging than conventional video training.

Furthermore, AR has been used for a personalized training experience, which is paramount for improving individual learning and skills (Kang et al., 2023; Somerkoski et al., 2020). For instance, Papakostas et al. (2021) examined the user experience, usability, and interactivity of a customized mobile AR training system. The authors used a modified technology acceptance model to investigate the main aspects affecting firefighters' acceptance of the system. A sample of 200 users evaluated the proposed system. This study found that usefulness is the strongest predictor of firefighters' intention to use the AR system. The authors also highlight that the AR platform is cost-effective, countlessly repeatable, and can offer a variety of real-life scenarios for high-risk environments.

Finally, AR technology has been used to enhance the realism and effectiveness of hands-on learning experiences and learning motivation (Khan et al., 2019). Brown et al. (2005) pointed out the advantages of AR in providing realistic effects to train fire support teams to locate fire targets. Arjoni et al. (2023) reported promising outcomes regarding the use of augmented environments as an alternative to real-life training scenarios. This aspect is particularly important in the context of firefighting training, where the safety and effectiveness of first responders are vital. Research conducted by Tarkkanen et al. (2020) developed an AR-based application to teach fire safety skills to children and check their learning gains. They plan to conduct more research to compare the AR platform with an equivalent VR system. Similarly, Kang et al. (2023) combined OST AR and VR to offer a realistic fire drill training system that trains people to use a physical fire extinguisher to put out a virtual fire before evacuating the premises. The study evaluated the effectiveness of the training by involving 21 participants to test the prototype and assess its usability. The users provided positive feedback on the usefulness, efficiency, and immersiveness of the system. The study showcased the potential of a balanced combination of AR and VR to improve fire safety training.

In summary, looking at the fire safety literature, AR training has been applied in only a limited number of studies, primarily focusing on comparisons with other training approaches. Knowledge gaps remain despite the positive and significant impact of AR tools on fire safety training and emergency preparedness reported in these studies. These include an understanding of the tangible impact of digital safety training across different people. Addressing these gaps underscores the purpose of this research, which aims to provide deeper insights and robust evidence on AR training's efficacy in fire safety. As such, this research evaluated the efficiency of AR safety training in terms of knowledge, self-efficacy, instructions quality, AR preference, perceived task load, tool usability, and usefulness. These self-reported metrics are widely recognized in the above AR and VR safety training research.

3. Methods

This research investigates the effectiveness of AR training in learning the proper use of a fire extinguisher based on the PASS operational procedure. Fig. 1 provides the research workflow. The first step of this work focuses on the development of an AR training tool, as described in Section 3.1. Subsequently, the proposed AR-based training was tested as described in Section 3.2. Qualitative and quantitative data were collected from volunteer participants (Section 3.3).

All responses were encoded, transcribed, and analysed thematically and statistically (Section 4).

3.1. AR system design

The AR training tool was designed for a tablet device (Samsung Galaxy Tab S8 + 5G model), and the development was undertaken using Unity (version 2022.3.3.f1) on a Windows 11 Family Laptop (64-bits, AMD Ryzen5 3500U, 16 GB RAM). Unity is one of the most widely used and reliable game engines integrated with AR development toolkits and plugins (Nigam, 2022; Wijesooriya, 2023). The tablet device is equipped with an Android 14 operating system (One UI 6.0), 8 GB of RAM, and 256 GB of internal storage. It features a 12 MP camera for image capture (photos and videos), with a 12.4″ screen size. It also includes integrated sensors such as an accelerometer, gyroscope, and magnetometer, weighing 572 g in total.

Some requirements must be met during AR application development to ensure a smooth real-time AR experience on a mobile device. These include the need for specific motion sensors, cameras, and hardware specifications, particularly concerning the device's CPU power. The selected tablet meets these conditions for AR integration and supports the ARCore SDK (Software Development Kit), enabling a markerless AR experience (i.e. without the need for physical markers such as QR codes (Hussien et al., 2020)). This capability is made possible by the device's use of Simultaneous Localization And Mapping (SLAM) technology, which allows it to recognize flat surfaces onto which holograms can be anchored. ARCore SDK was selected due to its comprehensive documentation available for developers and its support across various Android devices. Additionally, it is compatible with the Unity platform, allowing easy incorporation of multiple library packages into the project. More details on the settings requirements for AR mobile development and suitable manufacturer models for ARCore SDK can be found in (ARCore Google, 2024).

The prototype AR tool consists of a guided mission with five sequential tasks. The AR training requires participants to hold the tablet device in portrait orientation, stay aware of their surroundings, and accurately follow the on-screen instructions to complete the tasks. Through the tablet's screen, users can see the real world overlaid with digital objects and floating interactive buttons. Dynamic game instructions and other written content are shown in a fixed position at the top of the tablet display (see Fig. 2). The application also includes fire and powder-releasing sound effects. Once a user launches the

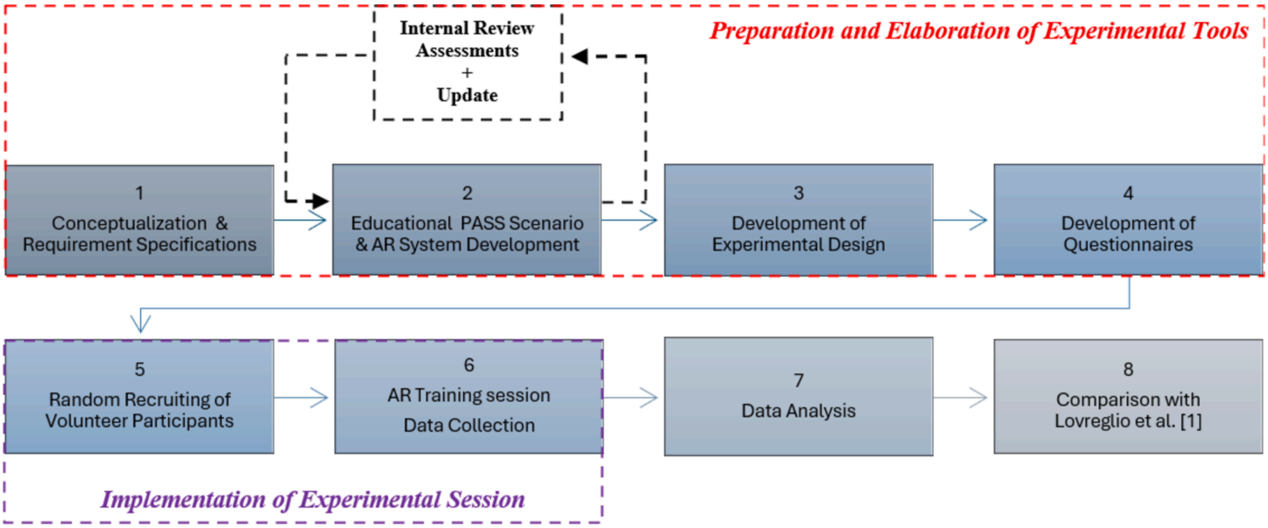
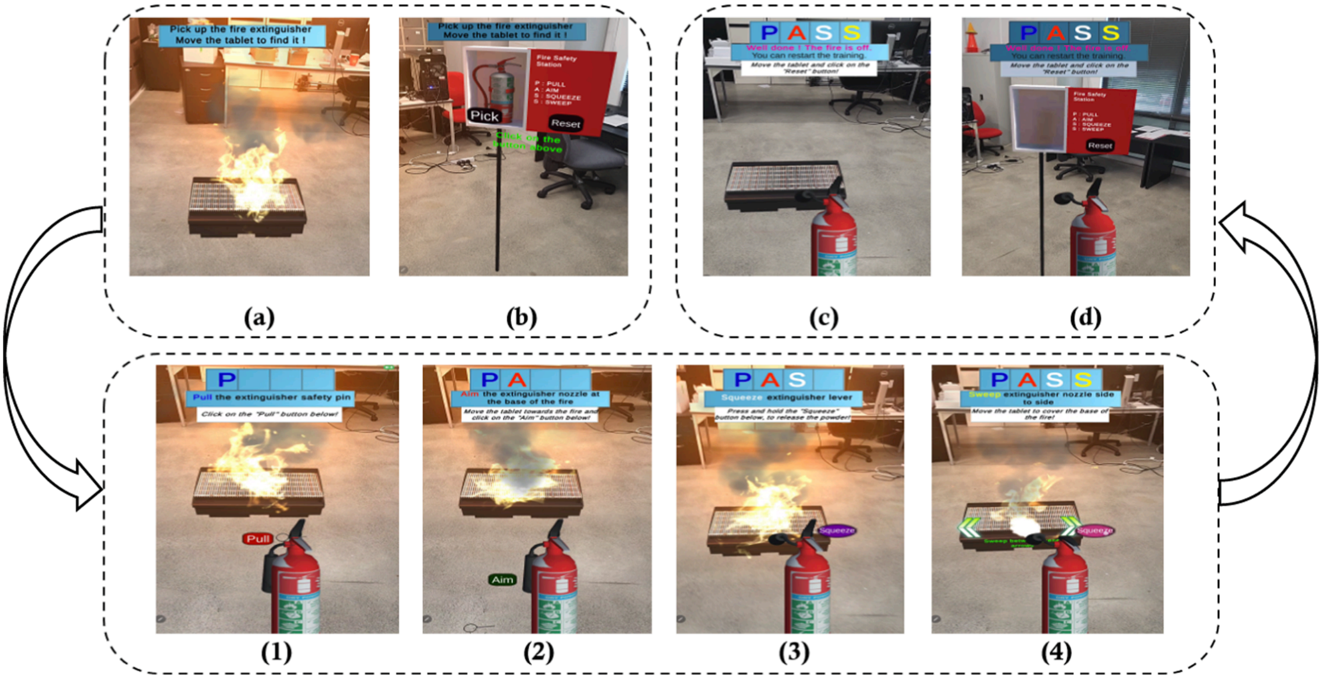


Fig. 1. Research process workflow.



Pick up the fire extinguisher
Move the tablet to find it !

Pick up the fire extinguisher
Move the tablet to find it !

Fire Safety Station

P : PULL
A : AIM
S : SQUEEZE
S : SWEEP

Click on the button above

Well done ! The fire is off.
You can restart the training.

Move the tablet and click on the "Reset" button!

Well done ! The fire is off.
You can restart the training.

Move the tablet and click on the "Reset" button!

Pull the extinguisher safety pin

Click on the "Pull" button below!

Aim the extinguisher nozzle at the base of the fire

Move the tablet towards the fire and click on the "Aim" button below!

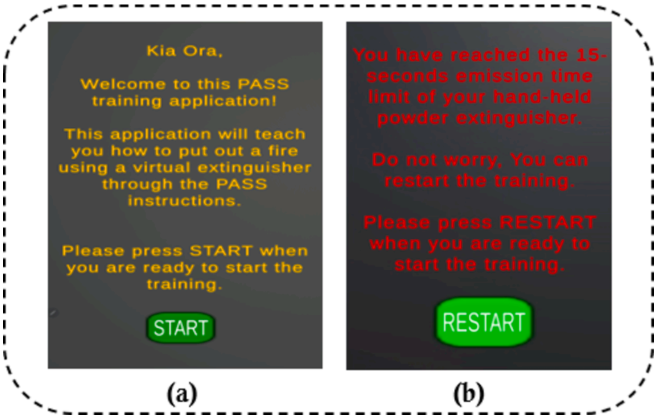
Squeeze extinguisher lever

Press and hold the "Squeeze" button below, to release the powder!

Sweep extinguisher nozzle side to side

Move the tablet to cover the base of the fire!

Fig. 2. Screenshots of the AR environment: (a) Burner on fire, (b) Fire extinguisher cabinet →(1 to 4) PASS procedure within (1) the Pull step asking the user to click on the pull button to release the safety pin of the extinguisher, (2) the Aim step asking the user to move the tablet towards the fire and to click on the aim button to orientate the nozzle at the firebase, (3) the Squeeze step asking the user to press and hold the squeeze button to release the powder inside the extinguisher, and (4) the Sweep step asking the user to move the tablet side to side covering the firebase →(c) Burner with fire suppressed, (d) Fire extinguisher station empty.



Kia Ora,

Welcome to this PASS training application!

This application will teach you how to put out a fire using a virtual extinguisher through the PASS instructions.

Please press START when you are ready to start the training.

You have reached the 15-seconds emission time limit of your hand-held powder extinguisher.

Do not worry. You can restart the training.

Please press RESTART when you are ready to start the training.

Fig. 3. Screenshots of the beginning and failure message: (a) Greeting message once the application is launched (Kia Ora in the Māori language translates as Hi), (b) Failure message once the fire extinguisher is empty of powder.

application, the training experience begins with a greeting message on the display (Fig. 3.a). When a user presses "Start", a burner on fire and a fire safety station (fire extinguisher cabinet) appear as holograms in the physical space (Fig. 2.a and 2.b). The five tasks and the instructions of PASS to put out the fire are as follows:

1) Pick up the fire extinguisher – First, users are required to visually search for the digital fire safety station in the real environment and then click on the "Pick" button near the fire extinguisher to pick it up (Fig. 2.a, 2.b);
2) Pull the safety pin – This is the first step of the PASS protocol. Users need to click on the "Pull" button shown near the fire extinguisher safety pin to trigger the pin removal animation (Fig. 2.1);
3) Aim the nozzle at the base of the fire – Subsequently, users must click on the "Aim" button displayed close to the fire extinguisher nozzle to trigger its movement animation toward the fire (Fig. 2.2), completing the second step of the PASS protocol;
4) Squeeze the lever – Then, to implement the third step of the PASS procedure, users need to press and hold the "Squeeze" button close to the fire extinguisher lever to release the extinguisher's powder (Fig. 2.3);
5) Sweep the nozzle side to side – Finally, users must move the tablet left and right while aiming at the fire's base. This step aims to ensure the powder jet sweeps across the entire burner surface, mimicking the operation of a real fire extinguisher (Fig. 2.4) and completing the PASS protocol.

Each task is completed once the user has performed the given instruction. The system then acknowledges the execution, deactivates the current instruction, and displays the next one. For instance, when instruction 2 is displayed, the "Pull" button appears (Fig. 2.1). The AR application is able to recognize the completion of the safety pin removal. Once the animation is finished, the system deactivates the display of instruction 2 and its respective "Pull" button and displays the next instruction 3 and its corresponding "Aim" button. Similarly, when the user extinguishes the fire, the AR application recognizes the completion of the PASS procedure, activates the display of the congratulation message (Fig. 2.c, 2.d), and tells the user that they may restart the whole training by clicking on the "Reset" button.

It should be noted that users may fail the mission. This occurs when the user fails to aim towards the base of the fire, and the fire continues to burn after the extinguisher's powder is fully depleted. In this case, the user is alerted with a text message, as shown in Fig. 3.b. The on-screen instructions, the fire surroundings (including the burner, flames, and smoke), the fire safety station, the fire extinguisher, and all the interactive buttons are seamlessly integrated with the real environment, creating a real-time AR experience. The size of the virtual flames decreases with prolonged contact with the virtual powder and increases when left without contact with the powder for a certain period.

Fig. 4 provides the operational and implementation framework of the AR system. The full experience was developed using C# scripting based

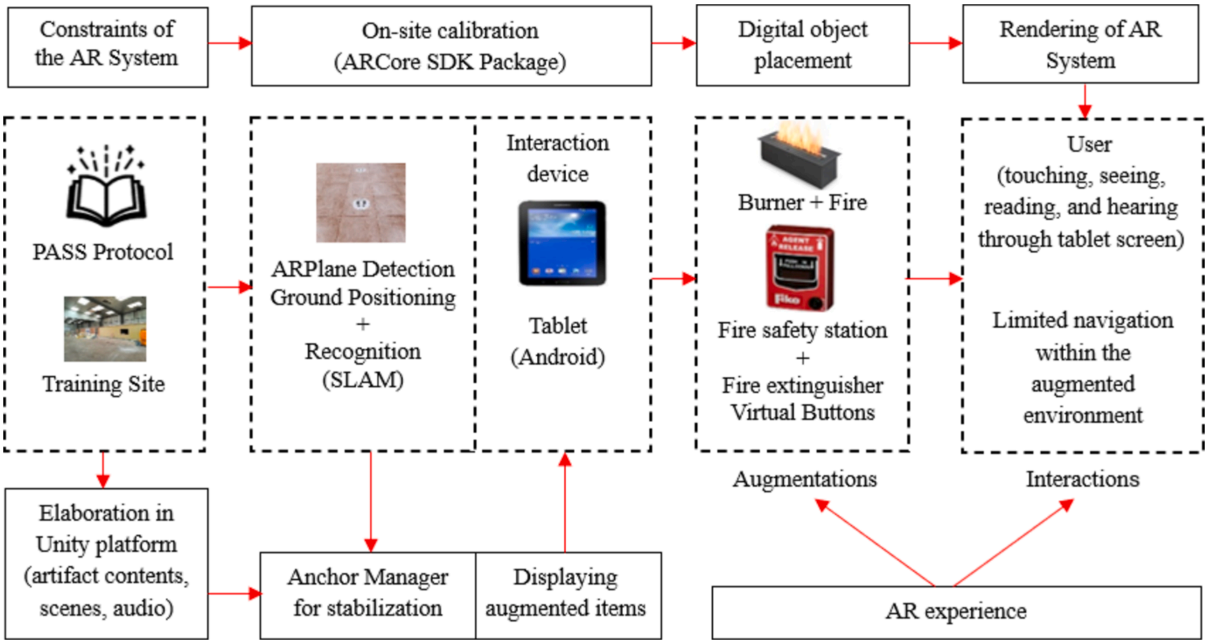


Fig. 4. Operational and implementation framework of the AR system.

on the training objectives of the PASS procedure. During development, calibration was carried out and tested several times to ensure the correct positioning of all digital objects (flames, smoke, burner, fire safety station, fire extinguisher, buttons, and text) on the training site. ARAnchor Manager from ARCore SDK was used to create an anchor for each object to increase their stability within the augmented environment. To ensure that the AR experience blended seamlessly with the physical environment, AR Plane Detection (integrated into the ARCore SDK) was used to detect the ground surface where the users were and place the burner and the fire safety station on it. The user sees the virtual burner on fire directly in front of them, with the fire safety station positioned to their right. The augmented environment can be easily modified to fit any floor layout, any workspace, and any experience requirements. Parameters such as flame regeneration rate, fire suppression speed, flame size, extinguishment duration, and powder amount inside the fire extinguisher may also be easily adjusted. Difficulty can be enhanced for further learning objectives (e.g. learning to recognize the class of the augmented fire and selecting the right extinguisher to suppress it).

It is important to note that the prototype can be customized for future developments. It can be adjusted using a framework, such as the XR Plug-in Management package from ARFoundation, which allows for managing and configuring the SDK's functionalities. This includes the ability to handle scripts and interactions via coded clickable buttons. Once the AR application is launched, the game controller instantiates the tablet's position as the origin point to place the virtual elements. Their geometric coordinates were defined during the development and can be adjusted. Unity's particle system was used to create and configure the flames, smoke, and extinguishing powder effects by adjusting dynamic parameters such as the size and intensity of particles. For the fire and powder-releasing sound effects, sound samples were downloaded from the Unity Asset Store, providing more realism to the experience. The fire extinguisher model was purchased and imported from Unity Asset Store. The burner furnace model was purchased and imported from the TurboSquid site. A control script was used to create the interaction between the released powder particles and the flame particles, ensuring that the fire was correctly put out only if the user aimed the nozzle at the base of the flames.

3.2. *Experimental test procedures*

The experimental procedure in Lovreglio et al. (2021) has been used in this study to investigate the pedagogical impact of the proposed AR application (described in Section 3.1). The data collected from the experiment were compared with those collected from a VR setup and a video setup reported in Lovreglio et al. (2021), where the same training was implemented through the VR and video methods. In other words, all three methods aim to teach users how to operate a fire extinguisher to put out a fire following the PASS procedure.

Fig. 5 shows the experimental design for the three different setups (AR, VR, and video training). The AR, VR, and video training methods are the independent variables (i.e., experimental conditions). Three data collection stages – just before training (pre-training), directly after training (post-training), and 3–4 weeks after training (retention) – were employed to assess users' learning performance. This 3–4 weeks duration gap is the most prevalent retention period in similar studies, including Paes et al. (2024) and Rahouti et al. (2021).

Participants were recruited randomly at Massey University (Albany campus) in New Zealand and received NZD $10 voucher cards as compensation for their time. Prior to the data collection, ethical approval was obtained from Massey University Human Ethics Committee: Southern A (No. 4000027646). At the beginning of the experiment, participants received a Participant Information Sheet and signed a consent form to indicate their agreement. Data collection took place during the experiment sessions in a laboratory (for pre- and post-data) and online about one month later (for retention data). Each session took approximately 20 minutes, resulting in a total of about 20 hours of training and data collection over seven weeks.

Each participant completed a survey questionnaire corresponding to each stage. The comparison (see Section 4) is based on quantitative dependent variables (i.e., participants' responses) collected in each experimental setup at each phase of the training experience (pre-training, post-training, and retention stages). These dependent variables were collected through sets of measurements using existing questionnaires (see Section 3.3). Participants were evaluated to measure their knowledge, self-efficacy, perceptions of the instructions' efficiency and

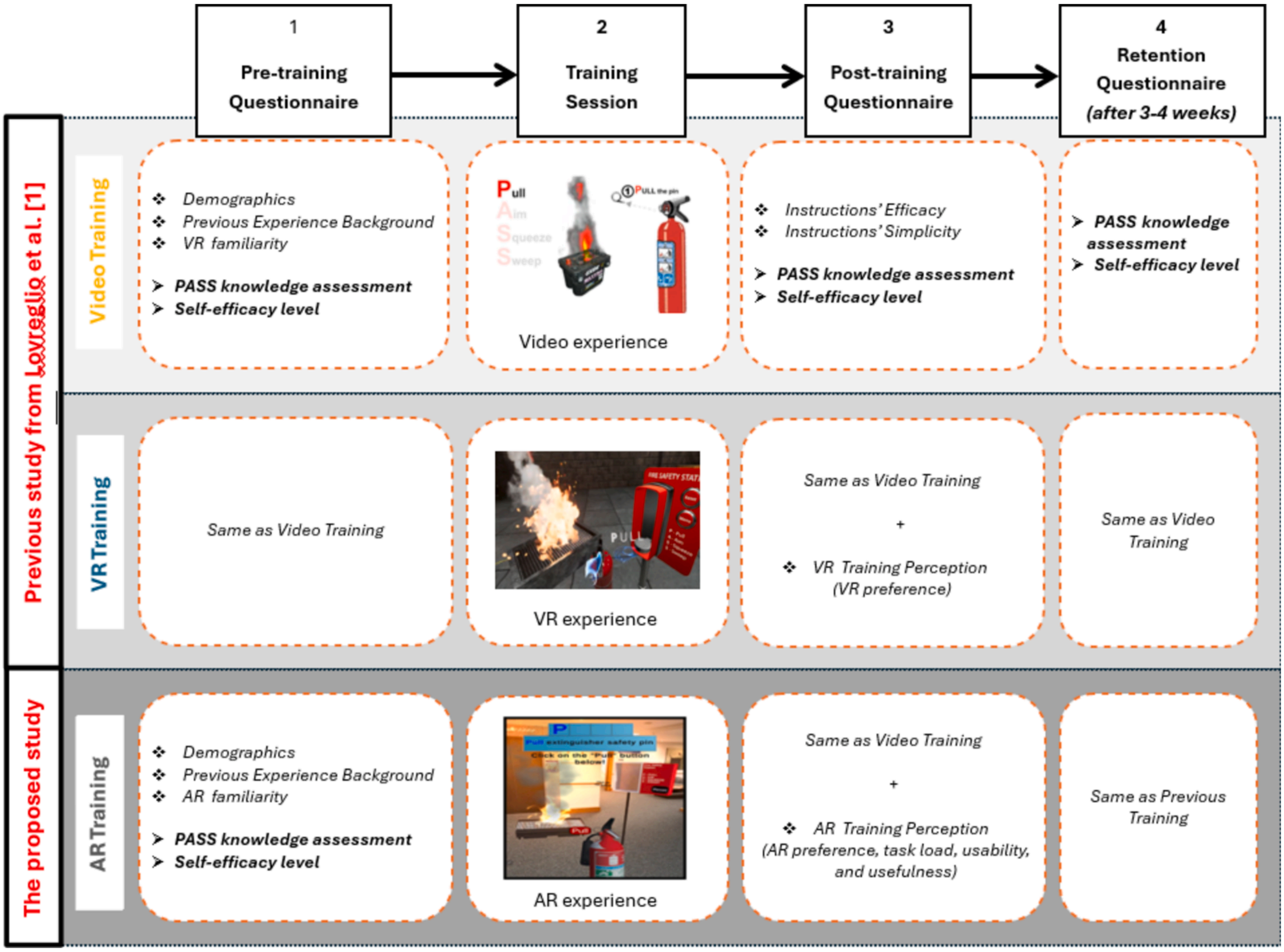


Fig. 5. Research experimental design structure for AR training (current study), video, and VR training (previous study in Lovreglio et al. (2021).

simplicity, task load, perceived usability, and usefulness of the system. Evaluating immediate knowledge acquisition and self-efficacy enhancement was achieved by testing the difference in the levels of these measurements between pre-training and post-training. In turn, knowledge and self-efficacy retention were assessed between post-training and retention.

3.3. Data collection instruments

Participants' responses were collected via three questionnaires answered by participants at the three experimental stages (i.e. pre-training, post-training, and retention). These were obtained just before, just after, and 3–4 weeks after training, respectively. Each questionnaire comprises a set of question clusters to gather information and feedback from participants.

Many measurement instruments such as user engagement, motivation, knowledge acquisition, and knowledge retention are used in literature to measure the effectiveness and impact of a training tool (Gong et al., 2024; Scorgie et al., 2024). In this paper, we compare knowledge acquisition and retention as well as self-efficacy and the quality of instructions. These metrics have been used in many similar studies to assess the effectiveness of training solutions (Lovreglio et al., 2021; Scorgie et al., 2024; Papakostas et al., 2021; Kang et al., 2023; Paes et al., 2024; Khan et al., 2019; Brooke, 1996; Davis, 1989). Further, these metrics were also selected to have a direct comparison of the AR training data collected in this study, with the data published in Lovreglio et al. (2021). The pre-training questionnaire involves the first four clusters (1 to 4), the post-training questionnaire includes clusters 3 to 9, and the retention questionnaire involves clusters 3 and 4.

1) A *Demographic* cluster comprised four questions to collect some general information on the users, including their gender (close-ended), age (open-ended), occupation (open-ended), and educational level (close-ended). These items were asked to verify that the sample of the AR training group is comparable to the sample of the other two training groups (VR and video) in Lovreglio et al. (2021).
2) A *Previous Experience and Background* cluster included four close-ended questions for collecting participants' previous experience in fire extinguisher training, fire extinguisher usage frequency, video game play frequency (i.e., how often they play video games on a tablet or smartphone), and previous AR technology experience. This information was used to check that the three training groups have similar levels of prior experience in order to avoid any bias in this study.
3) A *Knowledge* cluster encompassed two open-ended questions used to assess the participant's knowledge regarding the steps of operating a fire extinguisher to put out a fire. Open-ended questions were selected to allow participants to respond freely without the bias that multiple-choice or close-ended questions might impose. The questions are as follows: a) "Can you outline the specific steps involved in using a fire extinguisher? If so, please list them below", and b) "What should you pay attention to while putting out a small fire?". Based on

Table 1
Example of scoring procedure for the open-ended knowledge test.

Knowledge test questions	**Participant ID**					
	#1	#2	#3	#4	…	#60
Mention the PASS procedure name		1	1	1		
Pull the safety pin		1		1		
Aim the nozzle at the firebase			1	1		
Squeeze the lever			1	1		
Sweep side-to-side		1	1	1		1
Total Score	**0**	**3**	**4**	**5**	…	**1**

the number of distinct actions mentioned in their answers to the two questions, participants received a score between 0 and 5, manually coded by a researcher. These actions (detailed in Section 3.1) include: 1) Mention the PASS procedure name, 2) Pull the safety pin, 3) Aim the nozzle at the base of the fire, 4) Squeeze the handle lever, and 5) Sweep the nozzle side to side. For instance, if in question (a), participants mentioned tasks 2 and 5, and in question (b) mentioned tasks 1 and 5, they would receive a total knowledge score of 3, as actions 1, 2, and 5 are mentioned in both combined answers. The initial knowledge was assessed before the training, the knowledge acquisition was assessed just after the training, and the knowledge retention was assessed 3 to 4 weeks after the training. An example of a scoring procedure is provided in Table 1.

4) A *Self-efficacy* cluster included two close-ended questions to collect participant's confidence in their ability to use a fire extinguisher correctly. The two factors highlighted in these items are confidence in knowing the right actions to put out a fire and confidence in the ability to do them well. These factors were selected as they have been used in some literature related to fire safety training (Lovreglio et al., 2021; Paes et al., 2024). Ratings were collected and calculated using a 7-point Likert scale ("strongly disagree" = –3, "strongly agree" = +3), and answers were averaged to form the final self-efficacy score for each participant. The baseline self-efficacy level was assessed before the training, the self-efficacy enhancement was assessed just after the training, and the self-efficacy retention was assessed 3 to 4 weeks after the training.
5) An *Instruction Efficacy and Simplicity* cluster consisted of two and three questions, respectively, which were used to measure training-related factors. These questions gathered participants' perceptions of the quality of instructions provided during the AR training. Participants were asked to rate their level of agreement ("strongly disagree" = –3 to "strongly agree" = +3) for each of the following statements: a) The recommendations provided in the augmented experience were useful and relevant, b) The provided recommendations will allow me to effectively use a fire extinguisher, c) I could easily learn the recommendations provided in the augmented experience, d) I could easily remember the provided recommendations, and e) I could easily carry out the provided recommendations. Instruction efficacy was calculated by averaging the scores of items (a) and (b), while the instruction simplicity score was averaged from items (c), (d), and (e).
6) An *AR Preference* cluster included three close-ended questions to assess the participants' perception of AR technology compared with traditional training. Therefore, the AR group respondents were asked to rate their level of agreement ("strongly disagree" = –3 to "strongly agree" = +3) for each of the following statements: a) I found this AR training more engaging than traditional training methods (such as slide-based lectures, non-interactive videos, printed manuals and leaflets), b) It was easier to remember the instructions provided in this AR training than those provided in traditional training methods, and c) I prefer this AR training over traditional training methods. The scores of each item are provided separately.
7) A *Task Load* cluster consisted of six items modified from the NASA Task Load Index (TLX) (Hart, 1986) to measure the task load of participants while they were using the system. The items were used to collect perceived task load from participants during the AR training experience. This measure has been used by Paes et al. (2024) to assess an AR safety training application for building occupants. It aims to evaluate whether the perceived workload and ergonomic aspects of the AR system influence user performance. The task load addressed the following factors: a) the level of mental demand of the AR training, b) the physical demand of the AR training, c) the temporal demand of the AR training, whether rushed or slow, d) the participants' self-reported performance in completing the training, e) the level of effort required to perform the training, and f) the experienced feelings of frustration such as insecurity, discouragement, irritation, stress, and annoyance during the training. Ratings were collected and calculated using a 7-point Likert scale ("strongly disagree" = –3, "strongly agree" = +3).
8) A *Usability* cluster was composed of seven items from the System Usability Scale (SUS) (Brooke, 1996) to measure how usable the system is from the participant's perspective. This scale has been previously used in AR research by Kang et al. (2023) to test the suitability of user interfaces. The items were adapted from the literature to fit this study as follows: a) ease of use, b) cumbersome to use, c) comfortable experience, d) need for technical support, e) how well the user interface functionalities are integrated, f) suitability for keeping interest and attention, and g) the desire to frequently use the AR system. Ratings were collected and calculated using a 7-point Likert scale ("strongly disagree" = –3, "strongly agree" = +3). Answers were averaged to form the final usability score for each participant.
9) A *Usefulness* cluster consists of four items from the Technology Acceptance Model (TAM) (Venkatesh and Davis, 2000) to measure the perceived usefulness and utility of the system for participants. The assessing items were adapted from Davis (1989), including a) enhancing individual performance, b) improving individual response time, c) increasing self-confidence if regularly used, and d) recommending its usefulness to others. Ratings were collected and calculated using a 7-point Likert scale ("strongly disagree" = –3, "strongly agree" = +3).

Additionally, general assessment and improvement feedback were gathered in the post-training stage through open-ended questions, which included: a) "Please list 3 keywords that best describe your AR training experience", b) "Did the AR training meet your expectations? Please explain why", and c) "Please list any unclear aspects or concerns regarding the AR system that require further enhancement". The feedback data was transcribed into ordinal scales, and the outputs were analysed using descriptive statistics.

4. Results

Kolmogorov-Smirnov and Shapiro-Wilk tests were used to determine if the data for each dependent variable measured from the AR group followed a Gaussian distribution. Only the SUS data was normally distributed. All the participants' data scores are reported using boxplots or bar charts and analysed by experiment stages (pre-training, post-training, and retention) and conditions (the current AR training group and the previous VR and video training groups in Lovreglio et al. (2021).

SPSS (statistical analysis software) was used to analyse and compare knowledge, self-efficacy, and quality of instructions across three groups (AR, VR, and video). The analysis aimed to check whether there were any significant differences between these groups at different stages of the experiment. A within-group pairwise comparison was conducted for the AR training group using the Wilcoxon signed-rank test for non-normal variables. In this case, the responses of the same participant were assessed at three different times, and the data were matched interdependently. For the comparison across the AR group with the VR and video group, a between-group pairwise comparison was conducted for each experiment stage, using the Mann-Whitney *U* test for non-normal variables. In this case, the data across groups were treated as independent because each group held different participants.

Moreover, for all tests, Cohen's delta parameter (d) was used to check the effect size of differences across dependent (pre, post, retention) and independent (AR, VR, video) groups, in addition to p-values (Grissom and Kim, 2014). A significance level of 0.05 was assumed to derive the p-value within each comparison.

4.1. Participants' demographics

A sample of 60 participants took part in the AR training. This new sample consists of university students and staff from the Albany campus of Massey University, and it was randomly drawn from the same population used in the previous study by Lovreglio et al. (2021). Each group entirely consisted of unique participants without any overlap between samples. Fig. 6 provides an overview of the demographics and experience of the AR sample, as well as the VR and video samples used in Lovreglio et al. (2021). The results of the statistical tests in Fig. 6 show that there is no significant difference between the three samples in terms of age, sex, and experience using a fire extinguisher and video games. Three to four weeks after the training, the participants of the AR training were contacted by e-mail to complete the online retention test. Fifty-four participants (90 % of the sample) completed it.

The sample size for this experiment was determined using a power analysis named G*Power 3 (Faul et al., 2007). The analysis was carried out to detect a medium effect size (d = 0.5) between two independent groups. Setting a power of 0.8 and a significance level of 0.05, it was possible to identify a sample of 26 participants. However, it was expected that some of the sample would not take part in the retention part of this experiment. Given that the participant retention rate in Lovreglio et al. (2021) was close to 50 %, we decided to have at least 52 participants for our AR training experiment.

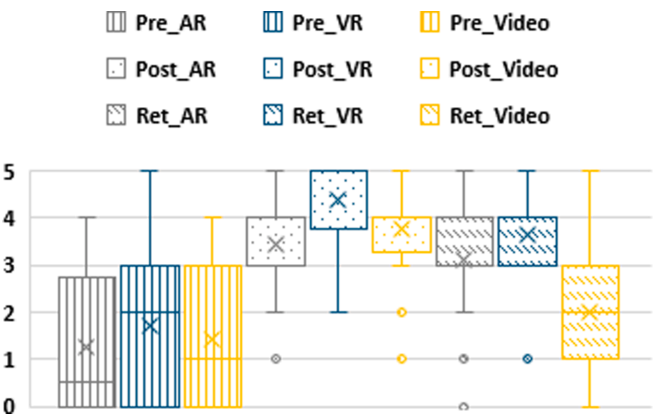
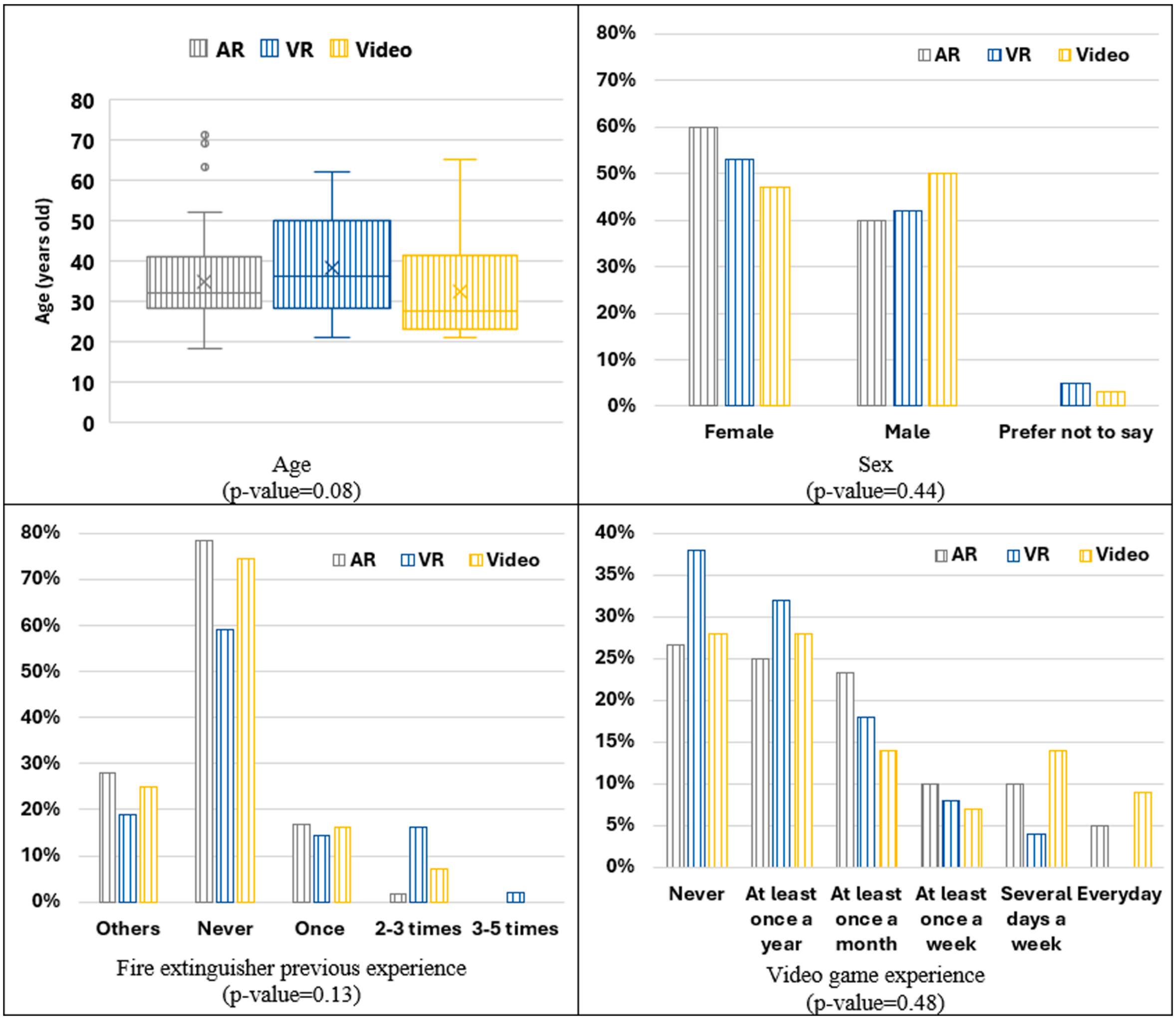


Fig. 7. Knowledge scores before the training (Pre), after the training (Post), and after 3–4 weeks (Ret), for the AR, VR, and video groups.



Age
(p-value=0.08)

Sex
(p-value=0.44)

Fire extinguisher previous experience
(p-value=0.13)

Video game experience
(p-value=0.48)

Fig. 6. Participants' demographics and previous experience: the VR and Video data are retrieved from Lovreglio et al. (2021).

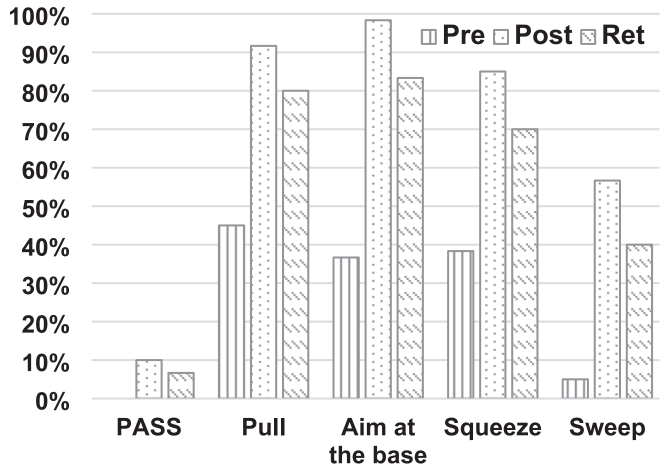


Fig. 8. Segregated knowledge data for each evaluated item in the AR group.

4.2. *Knowledge assessment*

In this section, Fig. 7 shows the knowledge scores of the AR group compared to the two other groups at different stages. Fig. 8 indicates the proportion of participants who knew information regarding the PASS procedure at the three experimental stages. It can be observed that only a few participants from the AR group forgot some information after 3–4 weeks; thus, their knowledge decreased a little over time. Finally, not many people have learned about the PASS acronym. This might be because the AR training was not designed to ensure that the participant remembered the PASS acronym through an interactive learning exercise (learning by doing). Indeed, as seen in Fig. 2, the PASS acronym was only highlighted in the AR system interface (i.e., visual learning instead of procedural learning experience).

Table 2 indicates that, for the AR group (pre vs post), the knowledge of participants before and immediately after the training had a statistically significant increment (p-value < 0.05), meaning that the training had a real impact on the outcomes observed. Similarly, it can also be noticed from Table 2 that there is a statistically significant decrease in knowledge when comparing the post and the retention scores.

In addition, a between-group analysis was carried out to determine whether there was any statistically significant difference between the groups regarding knowledge scores in the three experimental stages (Table 3). Results show that there was no statistical difference when comparing the initial knowledge of participants across AR, VR, and video (the p-value is well above the significance level of 0.05). It shows that the three groups started the experiment with a comparable level of expertise. Immediately after the training completion, the AR group acquired significantly less knowledge than both the VR and video groups. Finally, the knowledge for the AR group 3–4 weeks after the training is statistically greater than the video group and statistically lower than the VR group. The effect sizes in Table 4 provide an overview of the impact of the three training methods on knowledge acquisition and retention.

Table 2
Within-group comparisons of knowledge scores before training (Pre), after training (Post), and after 3–4 weeks (Ret), for the AR training condition (Wilcoxon test with a significance level of 0.05).

	Pre vs Post	Post vs Ret
N	60	54
Z	−6.328	−2.518
P-value	**<0.001**	**0.012**
Cohen’s d	1.885	−0.334

Table 3
Between-group comparisons of knowledge scores before the training (Pre), after the training (Post), and after 3–4 weeks (Ret), for AR vs VR and AR vs Video training conditions (Mann–Whitney u test with a significance level of 0.05).

	Stages		
Between-group comparisons	*Pre*	*Post*	*Ret*
Mean – AR group	1.3	3.4	3.1
SD – AR group	1.4	0.8	1.0
AR versus VR			
N	108	108	74
Z	−1.237	−4.614	−2.413
P-value	0.216	**< 0.001**	**0.016**
Cohen’s d	−0.274	−1.034	−0.525
AR versus Video			
N	105	104	78
Z	−0.529	−2.477	−3.468
P-value	0.597	**0.013**	**< 0.001**
Cohen’s d	−0.107	−0.401	0.982

Table 4
Cohen’s effect sizes for knowledge acquisition (Pre vs Post scores) and knowledge retention (Post vs Ret scores).

Training type	Knowledge acquisition Cohen’s d	Knowledge retention Cohen’s d
AR	1.885	−0.334
VR	1.986	−0.756
Video	1.952	−1.574

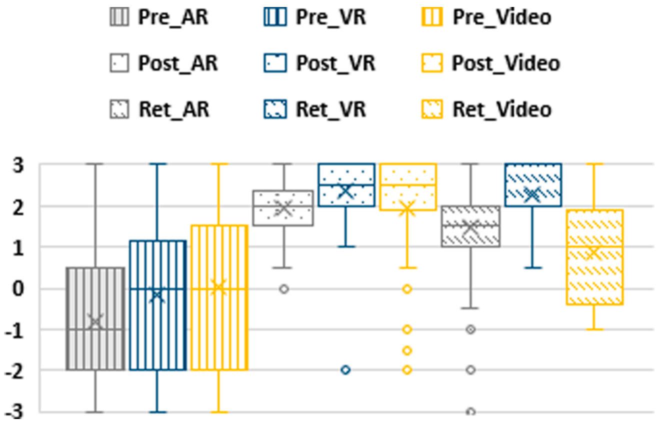


Fig. 9. Self-efficacy scores before training (Pre), after training (Post), and after 3–4 weeks (Ret), for AR, VR, and video groups.

Table 5
Within-group comparisons of self-efficacy scores before the training (Pre), after the training (Post), and after 3–4 weeks (Ret), for the AR training condition (Wilcoxon test with a significance level of 0.05).

	Pre vs Post	Post vs Ret
N	60	54
Z	−6.561	−2.716
P-value	**<0.001**	**0.007**
Cohen’s d	2.159	−0.483

4.3. *Self-efficacy assessment*

In this section, Fig. 9 shows the self-efficacy scores of the AR group compared to the two other groups at different stages. Fig. 9 and Table 5 show that the self-efficacy scores of participants just after the AR training are statistically greater than the initial self-efficacy scores (p-value < 0.05). That means that the training had a real impact on the outcomes observed. Similarly, the long-term self-efficacy score is a little statistically lower than the post-training one. Moreover, there was a

Table 6
Between-group comparisons of self-efficacy scores before the training (Pre), after the training (Post), and after 3–4 weeks (Ret), for AR vs VR and AR vs Video training conditions (Mann–Whitney u test with a significance level of 0.05).

	Stages		
Between-group comparisons	*Pre*	*Post*	*Ret*
Mean – AR group	−0.8	1.9	1.5
SD – AR group	1.6	0.7	1.1
AR versus VR			
N	106	106	74
Z	−1.619	−3.550	−3.009
P-value	0.106	**< 0.001**	**0.003**
Cohen's d	−0.365	−0.544	−0.730
AR versus Video			
N	106	106	78
Z	−2.301	−1.894	−2.471
P-value	**0.021**	0.058	**0.013**
Cohen's d	−0.480	−0.004	0.544

Table 7
Between-group comparisons of instructions efficacy and simplicity scores for AR vs VR and AR vs Video training conditions (Mann–Whitney u test with a significance level of 0.05).

	Quality of instructions	
Between-group comparisons	*Efficacity*	*Simplicity*
Mean – AR group	2.0	2.0
SD – AR group	0.8	0.8
AR versus VR		
N	106	106
Z	−2.943	−3.018
P-value	**0.003**	**0.003**
Cohen's d	−0.525	−0.491
AR versus Video		
N	104	104
Z	−0.054	−0.823
P-value	0.957	0.410
Cohen's d	0.178	−0.026

statistically significant difference between the AR and the VR training groups for the post-training and retention periods and between the AR and the video training groups for the pre-training and retention periods (see Table 6). These outcomes suggest that the observed differences are unlikely to be due to a random assignment or chance alone. Additionally, there is no statistically significant difference between AR and VR in the pre-training stage and between AR and video in the post-training stage.

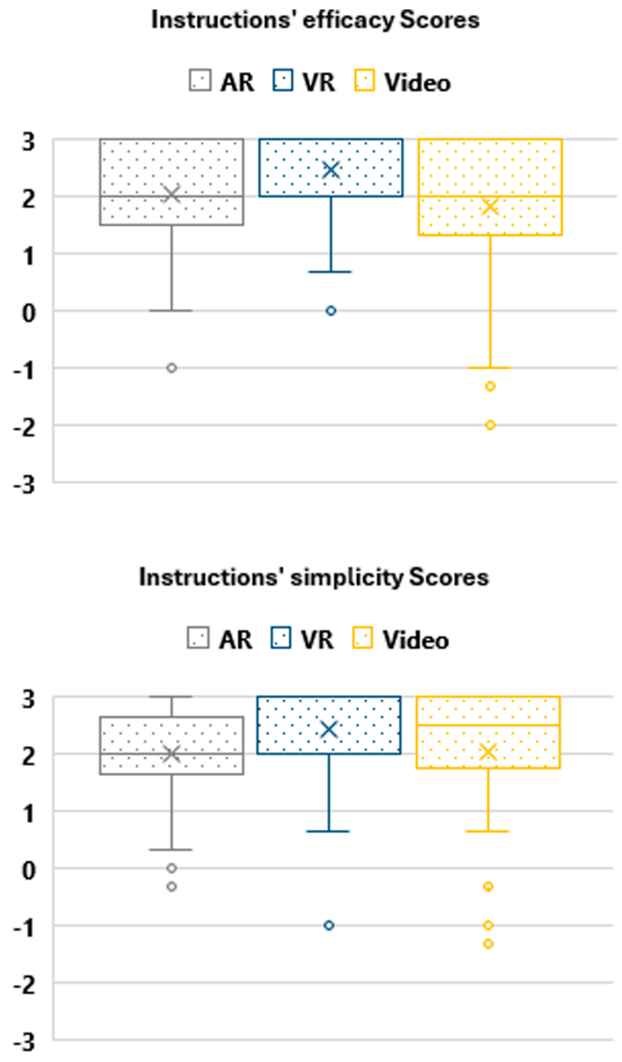


Fig. 10. Instructions efficacy and simplicity scores for the AR, VR, and Video groups.

Fig. 11. Qualitative words cloud from participants' experience report.

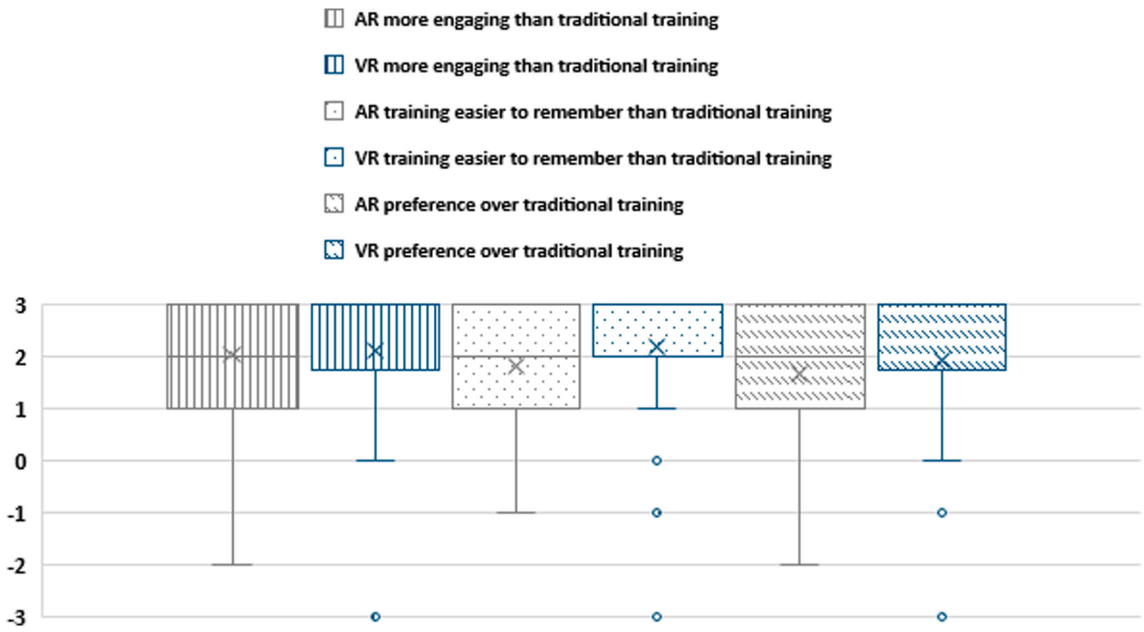


Fig. 12. AR and VR training perception assessment against video training.

4.4. *Instructions' efficacy and simplicity assessment*

In this section, Fig. 10 shows the instructions efficacy and simplicity scores of the AR group compared to each of the two other groups. Fig. 10 and the statistical tests in Table 7 show that the instructions efficacy scores of participants in the AR training are statistically greater than those in the video training but statistically lower than those in the VR training ($p\text{-value} < 0.05$). Also, the instructions simplicity scores in the AR training are not statistically different from the VR and video training ($p\text{-value} > 0.05$).

4.5. *Training perception assessment*

This section illustrates how participants in both the AR and VR groups perceived their training methods compared to traditional training methods. Qualitatively described in Fig. 11, the perception of participants who tried AR was very positive. Fig. 12 indicates that the great majority of those participants found AR training to be more engaging and easier to remember, and preferred it over traditional video training. Over 70 % of the sample provided a score greater than two for all three statements comparing AR training with traditional training, showing that most participants would prefer using an AR-based fire safety training tool over traditional training methods.

4.6. *Task Load, Usability, and Usefulness assessment*

This section provides an assessment and analysis of the participants' feedback regarding the task load, the usability, and the usefulness of their training experience from the AR group. Fig. 13 illustrates the scores rated by the participants for each measured variable. The results indicate that most participants were not mentally or physically overwhelmed with the AR system, as over 60 % provided an average TLX score below zero. Also, most of them (over 65 %) were at least somewhat satisfied with the usability of the AR system. Finally, the data indicate that all the participants felt that the prototype was useful, according to the global average of perceived usefulness.

5. Discussion

This study describes the development and evaluation of an AR-based tool to train people on how to use a fire extinguisher properly and to investigate the impact of this training on delivering knowledge of the PASS procedure. The work also compared the effectiveness of this AR training with the VR and video training versions reported in Lovreglio

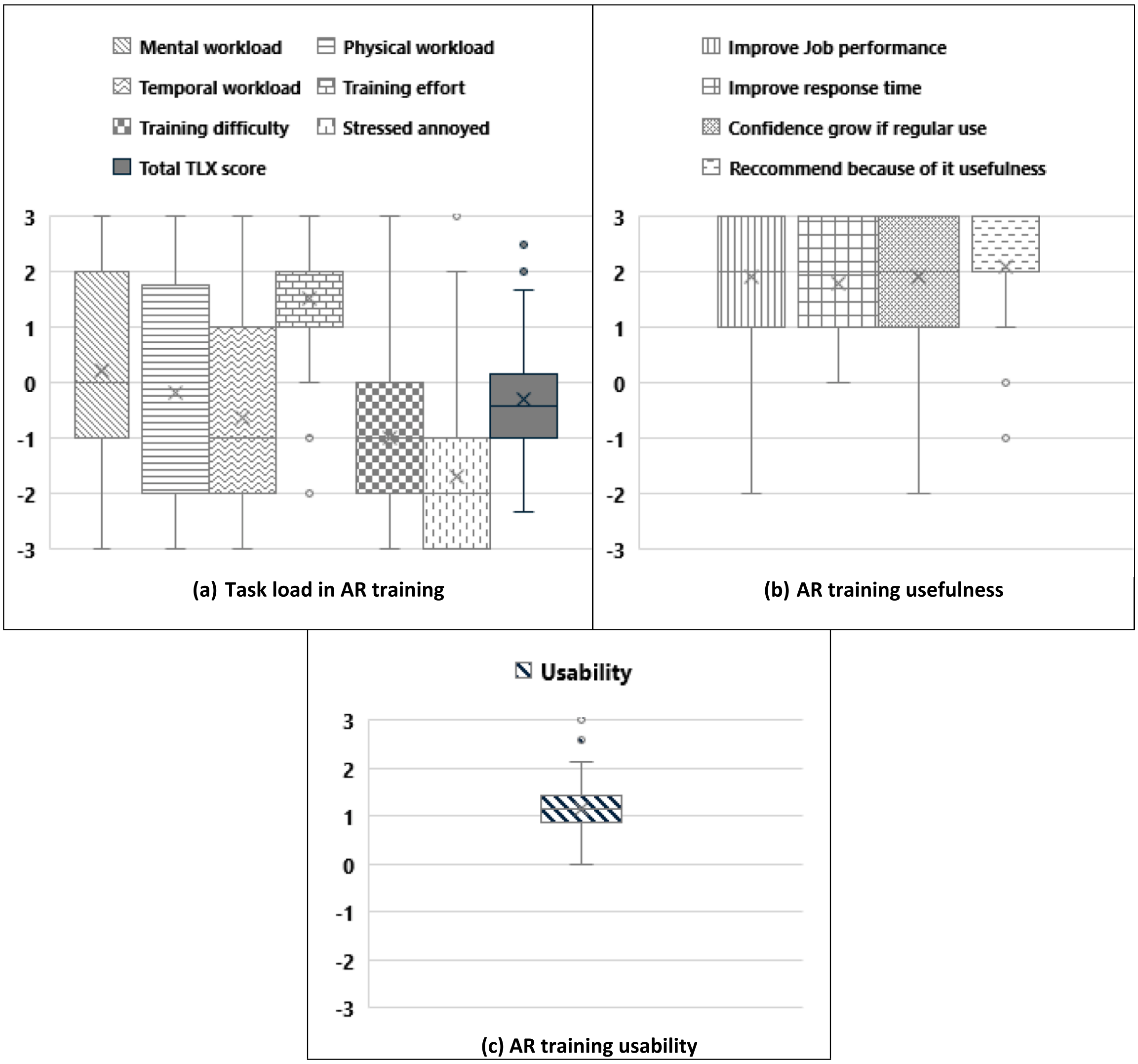


Fig. 13. Task load, usability, and usefulness scores for the AR group.

et al. (2021). Knowledge acquisition and retention, self-efficacy, and instructions' quality were the measured variables for the comparison. In this study, we chose Lovreglio et al. (2021) as the baseline for evaluating AR-based fire safety training as the authors focused on the same learning objective (i.e., the use of the PASS procedure to operate a fire extinguisher). Further, it was possible to run the comparison without having any sample bias, as both studies drew samples from the same population by recruiting participants at Massey University's Albany campus in Auckland, New Zealand, and participants in this study were distinct from those recruited in the related previous study. As such, this work represents one of the first attempts to compare AR safety training with VR and video training. This comparison was carried out in terms of several metrics: knowledge acquisition and retention, self-efficacy, and the efficacy and simplicity of instructions.

This research highlights the pedagogical potential of AR for procedural safety training and its impact on long-term knowledge retention. Indeed, the results in Fig. 7 and Table 2 show that AR generated a significant increment in knowledge with a large effect size (1.885) and a relatively small drop in knowledge retention, which is illustrated by the small effect size (−0.334) in Table 2. When comparing the results of the AR training with the VR and video training, it can be seen that knowledge acquisition for both VR and video training was significantly higher than that observed for the AR training (see Table 3). In contrast, AR training performed better in knowledge retention than video training. However, VR training outperformed AR training in this area. When comparing the effect sizes for the three training methods (see Table 4), it is observed that these are similar regarding knowledge acquisition. However, the effect sizes for knowledge retention show major effects for video training (−1.574), a moderate effect for VR training (−0.756), and a small effect for AR training (−0.334). This indicates that the participants of the AR training had a smaller decrease in knowledge.

Subsequently, the self-efficacy results illustrate that AR training has a significant impact in increasing these metrics. A major significant increment can be observed after the training and a small but significant decrease in self-efficacy is also seen in the retention stage (see Table 5). When comparing the self-efficacy data of the AR training with the VR and video training, it can be observed that VR training generates the highest self-efficacy scores after the training and at the retention stage (see Table 6 and Fig. 9). On the other hand, there is no significant difference between the self-efficacy for AR and video groups after the training, while the AR self-efficacy scores are significantly greater than the video scores in the retention stage.

The results also focus on the assessment of the quality of the instructions provided. In this regard, the present study found that AR training outperformed video training in the efficacy of instructions. However, the efficacy and simplicity of the instruction were slightly lower in the AR group than in the VR group, with a statistical difference between them. The instructions' quality scores were notably high in all training conditions, demonstrating that participants found the "guided procedural tasks" approach in video, VR, and AR formats to be highly efficient and easy to follow, regardless of whether it was experienced passively (i.e., watching a video) or actively (i.e., performed through VR or AR). These results suggest several implications for the design of AR systems. Interaction design should aim to improve user engagement and understanding, possibly by incorporating more intuitive and interactive elements. This could include auditory and haptic feedback, to simulate more realistic training scenarios.

From the perception point of view, AR participants were asked to rate their perceptions of the AR training compared to video training, as VR participants did in the previous study by Lovreglio et al. (2021). The results (Fig. 11) indicate that most participants preferred AR technology over traditional tools, but VR participants in Lovreglio et al. (2021) perceived VR technology even more positively than the conventional video method. Some findings also align with existing literature which noted that AR technology may not surpass VR technology or traditional methods in terms of involvement (Verhulst et al., 2021) and perception (Wang et al., 2023). Fig. 12 highlights the reasons why AR participants preferred AR training more than video training. The results show that there is great potential for the use of Extended Reality (XR)-based safety training instead of video-based safety training from the users' perspective. Despite the acquired knowledge in the AR experience being less than that of the two previous methods, more than 85 % of participants in the AR condition appreciated the functionality of the augmented training for learning procedural instructions. This outcome aligns with the findings of Alessa et al. (2023), where authors reported that the AR system is well designed for demanding procedural tasks, reinforcing long-term reaction response skills. However, participants indicated the need to enhance the AR application in terms of game content (learning the type of fire extinguisher to use according to the type of fire). The current application does not allow participants to select the suitable fire extinguisher type according to the fire class (A to F). Moreover, the application does not propagate the fire throughout the user's surroundings over time. The fire is just kept on the burner regardless of the obstacles around it. With such enhancements, the application could promote more realistic behavioural conditions, such as inducing stress to quickly put out a fire due to its propagation over time. Then, it may improve the realism of the training. Additionally, participants commented that they would like to use a physical fire extinguisher to be sure they could easily manipulate it, given its weight and the real stress of dealing with a fire.

Finally, this research also investigated how the participants perceived the AR training regarding its usability, its usefulness, and the participants' task load. The results from the task load survey indicate that this training method was generally not physically or mentally demanding, and participants experienced minimal difficulties, stress, or annoyance during training. The technology was judged easy to use, with the device being comfortable to hold, but a few participants mentioned that they would need technical assistance. These results suggest that the AR training tasks were easy to complete for most participants, which could explain why they performed similarly in knowledge acquisition and retention after the AR training. Moreover, usefulness scores were notably high in the AR training condition, demonstrating that participants found it to be beneficial for fire safety preparedness.

6. Conclusion

The main objective of this study was to assess the effectiveness of VST AR for safety training and to compare this solution with VR and video training. To achieve this objective, an AR-based fire extinguisher training system was developed and compared with findings from Lovreglio et al. (2021), who studied the effectiveness of VR-based fire extinguisher training and an existing training video. The three training solutions aim to teach users how to operate a fire extinguisher to put out a fire following the PASS procedure. They focus on domestic or workspace fire hazards. Sixty volunteers participated in this AR study, and the comparison with VR and video was based on data gathered via user-centred surveys and analysed with reliable tests to provide valuable insights about the effects of augmented reality on training.

This study shows that AR is effective for procedural safety training by significantly improving knowledge acquisition and having a small effect size in terms of how much participants forgot after three weeks. When comparing the three trainings, the findings suggest that immediately following the training, AR outperformed traditional video training in terms of knowledge retention, long-term self-efficacy, and instruction quality. However, while the AR experience was less effective than the VR experience in all these areas, the AR group experienced a smaller decline in knowledge retention over time.

In terms of self-efficacy, AR significantly increases scores, but VR achieves the highest self-efficacy both immediately after training and at the retention stage. AR instructions were more effective than video instructions but slightly less effective than VR instructions. Finally, all training formats received high ratings for instruction quality. These findings suggest that AR is a promising training option. Improvements could be made by incorporating more intuitive and interactive elements, such as auditory and haptic feedback, to enhance user engagement and simulate more realistic training scenarios.

It should be noted that this work did not investigate the ability of participants to operate a real fire extinguisher effectively. Moreover, the AR application used in this study lacked other types of sensory inputs, such as voice-over features (e.g., audio instructions), olfactory feedback (e.g., burnt smell), and haptic feedback (e.g., vibration or heat sensation). Therefore, future studies may explore the impact of engaging these other senses in performing the PASS procedure tasks. Additionally, a comparison between the two main types of AR devices (VST and OST) is needed to verify whether AR smart glasses (instead of handheld mobile devices) could provide ergonomic benefits to enhance the training experience and outcomes. Finally, future research may also explore further human-computer interaction aspects, such as sensory inputs, human factors, and behaviours, to investigate whether these aspects could impact and improve the effectiveness of AR fire safety training.

Ethical approval form

Massey University Human Ethics Committee in New Zealand: Southern A (No. 4000027646) reviewed and approved this research. Participants were briefed about the study's purpose through a participant information sheet, and all volunteers signed a consent form for data collection and storage before participating. They were also informed of their ability to withdraw from the study at any time without needing to provide reasons. The experiments were overseen by at least one researcher.

CRediT authorship contribution statement

Lorraine I. Domgue K: Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Daniel Paes:** Writing – review & editing, Visualization, Validation, Resources. **Zhenan Feng:** Writing – review & editing, Visualization, Validation, Resources. **Susan Mander:** Writing – review & editing, Visualization, Resources. **Selim Datoussaid:** Writing – review & editing, Supervision, Resources. **Thierry Descamps:** Writing – review & editing, Resources. **Anass Rahouti:** Writing – review & editing, Resources. **Ruggiero Lovreglio:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Methodology, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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