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Prototyping and testing a virtual reality counterterrorism serious game for active shooting

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ABSTRACT

An active shooting emergency requires an effective strategy to increase the chances of survival of the attacked population. Educational environments are one of the most common locations of such events. To reduce the impact of these disasters, several emergency plans have been developed and put in place. Traditionally, these emergency plans are taught to occupants using non-interactive videos, drills, etc. However, these conventional methods present many limitations regarding trainees' knowledge acquisition, engagement and self-efficacy. To overcome them, this paper presents the prototype of an immersive Virtual Reality (VR) Serious Game (SG) for counterterrorism training. A user-centred evaluation of the proposed training SG was conducted with 32 participants. The experiment aimed to investigate the impact of the proposed tool on participants' knowledge regarding the safest actions to take in case of an active shooter attack. Participants' intrinsic motivation and self-efficacy levels were also assessed before and after the VR-based training. Findings indicate that participants' knowledge, intrinsic motivation, and self-efficacy significantly increased immediately after the training.

1. Introduction

Terrorism attacks and active shooter events are becoming more common worldwide, resulting in hundreds of deaths and injuries [1,2]. Recent examples such as the mosque shooting in Christchurch (2019), the church shootings in Sutherland, Texas (2017), in Charleston, South Carolina (2015), and at an outdoor concert in Las Vegas (2017) – the deadliest mass shooting in modern US history – highlight the need to train people on the recommended actions to take in such disastrous events. These events are inherently unpredictable, but a closer investigation of recent events can provide solutions for mitigating fatalities and injuries.

Recent studies [3–5] revealed that active shooter events have most often occurred in businesses, followed by educational environments (schools and higher education institutions), open spaces (including public libraries) and government properties. The concerning statistics on active shooter events (see, for instance Refs. [5,6]) have prompted several governmental agencies to publish guidelines and recommendations that can be followed where these events occur in order to protect buildings and occupants [2]. Normally, these counterterrorism safety recommendations are taught through conventional methods such as non-interactive videos, drills, practices of "shelter in place" and "run-hide-fight" strategies, slide-based lectures, seminars, etc. [7]. However, many of these training

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methods present critical limitations in terms of trainees' learning performance, as shown in the fire safety domain [8,9]. In fact, from a pedagogical perspective, it is difficult to ensure that people trained through traditional drills receive sufficient instructions for all the actions they may need to perform in a real incident [9]. Moreover, people in traditional drills do not receive individual feedback on their performance, which can further jeopardise the effectiveness of training [9]. Another major limitation of conventional methods is the lack of life-like scenarios. It is risky, dangerous, and unethical to expose people to actual hazardous events. Without practising in similar scenarios, it is missing a piece in the process of experiential learning, which is harmful to translating knowledge into actions [10].

Unlike other emergencies, the duration of active shooter events is very short, with about 70% of the incidents ending within 5 min [2]. Therefore, people exposed to such threats may need to largely rely on themselves to ensure their safety and the safety of people under their responsibility. This highlights the importance of enhancing building occupants' preparedness to apply the countermeasures and respond efficiently and quickly before the arrival of first responder teams [2]. Despite the various training programs designed to increase occupants' awareness and preparedness, training has been unsatisfactory in many locations [2,11].

With the lack of training of building occupants, the inefficiency of existing training methods, and the increasing number of terrorist attacks, traditional and proactive training methods that respond to these challenges become necessary [2,9]. Serious Games (SGs) could provide a solution to face these new challenges. SGs are video games specially designed for educational purposes. SGs have been used effectively in several areas, including scientific education, medical and health, military training, natural disasters, fire evacuation, terrorism, sports, manufacturing, and construction [12,13]. In turn, Virtual Reality (VR) is an advanced visualisation technology that enables users to be immersed in a virtual environment. VR-enabled SGs allow users to undergo hands-on training in a simulation without exposing them to actual danger. Combining VR and SGs represents an alternative to conventional training to support existing training programs and bridge their gaps by providing a cost-effective and rapid training solution that can be provided worldwide [13]. VR and SG technologies have been increasingly used to support conventional training for emergencies and natural disasters [14–17] and safe evacuation from buildings [13]. Featuring the capabilities of VR and SG technologies, VR SGs can afford experiential learning, fulfilling the four learning stages (i.e., experiencing, reflecting, abstracting, and acting) of a complete cycle [18]. VR SGs provide interaction, immersion, and authenticity in a learning environment. Benefiting from this, learners can engage in tasks, make decisions, transfer knowledge into actions, observe consequences, and reflect on decisions and actions [19]. Finally, an immersive learning environment has the potential to outperform a non-immersive learning environment in terms of memory recall [20]. In other words, people are more likely to recall what they have experienced in an immersive virtual environment. As such, memory recall due to an immersive experience can enhance the effectiveness of training in terms of knowledge retention, as shown in previous safety training studies [21,22].

Various applications for counterterrorism and active shooting scenarios preparedness have been developed in the last decade using VR and SG approaches. For instance, Awada et al. [23] used a VR SG to investigate human behaviour and perception in an active shooter experiment using different navigation setups. The V-Armed tool [24] is one of the recent examples of training applications, which recreates several real-life shooter and hostage scenarios in which police officers must subdue a virtual target without endangering the lives of civilians. Other interesting applications are Standoff [25], EDGE [26] and AUGGMED [27], which were developed for counterterrorism training and will be described later in this paper (readers can refer to Section 2.4). The main purpose of the above-outlined applications was to help train counterterrorism officers, aid workers and first responders. Thus, they are not directly aimed at training the public in educational environments such as schools and universities. The only existing case study for public training was proposed by Chittaro and Sioni [7] for a bombing attack at a train station. To the best of the authors' knowledge, no existing study has investigated the effectiveness of VR SG in terms of trainees' knowledge acquisition regarding the recommended actions to take in active shooter incidents, as well as changes in users' intrinsic motivation (i.e., the performance of an activity for the inherent satisfaction with the activity itself), and self-efficacy (i.e. perceived capabilities for learning or performing actions) towards training on these actions. Therefore, more research is needed to test the effectiveness of VR SG applications in this area.

The aim of this paper is to discuss the advantages and limitations of the combined use of VR and SGs to prototype training applications to enhance the counterterrorism preparedness of buildings occupants for educational institutions. This was achieved through two research objectives. The first was to prototype an immersive simulator to train users on the best actions to take in active shooter attacks. The prototype was developed for an educational environment, one of the most common environments where shootings have occurred in the past, as illustrated in Section 2. The second objective was to evaluate the proposed training prototype by assessing its effectiveness in terms of participants' knowledge acquisition and changes in participants' intrinsic motivation and self-efficacy.

2. Background

2.1. Active shooter events

International statistics highlight that some countries, such as the United States (US), are more affected by active shooter events. The US has a staggeringly high number of active shooter incidents compared to other developed nations. The US National Library of Medicine and National Institutes of Health released a study in 2016 that found that the US had more public mass shootings than any other of the 170 nations investigated [4]. Educational institutions (EIs) are the second location where active shooting events occur in the US [5]. The press reported that there had been at least 288 shootings in the US EIs between January 2009 and May 2018 [28]. Another investigation reports the statistics of EIs shootings since 2009, showing that the US has the most incidents (288 incidents), followed by Mexico (8), South Africa (6), India (5), Pakistan and Nigeria (4 incidents each), Afghanistan (3) and finally France, Canada and Brazil (2 incidents each) [29]. Katsiyannis et al. [30] report that more people have died or been injured in mass EIs shootings in the US in the past 18 years than in the entire 20th century. Statistics from a database going back to 1970 show that 2018 was by far the worst on record for gun violence in the US, with 94 school shooting incidents, a near 60% increase from the previous high record (59 in 2006) [31].

These statistics reveal an urgent need for solutions to mitigate the number of fatalities and injuries associated with active shooting events. One of these solutions is to educate people on the actions they need to perform where such an incident occurs.

2.2. Shootings management methods in educational institutions

Due to the increase of shootings in educational institutions worldwide, many have sought to develop emergency management plans (or procedures). For instance, since 2016 in France, schools have been required to stage simulated attacks to prepare children for potential active shooter attacks. Each school is required to hold three exercises per academic year, covering the ability of schools to react appropriately. In 2017, schools started to perform 'lockdown' drills in Singapore, with teachers and students locking themselves in classrooms and hiding from potential shooters. The US Army and the Department of Homeland Security designed simulations of school shooting situations for teachers. Multiple players take the role of a teacher trying to keep students safe during a shooting while a law enforcement officer tries to apprehend the shooter. These examples, among many others, highlight the increased interest from governmental authorities in developing solutions to prepare the population for such an event.

In 2013, the US Federal Guide for Developing High Quality School Emergency Operations Plans [32] specifically identified the "Run-Hide-Fight" as the standard response to acts of violence such as active shooting. This guide was endorsed by the US Department of Education, the US Department of Homeland Security, the Federal Emergency Management Agency and the US Department of Health and Human Services and was established as the standard terminology for describing what to do in an active shooting situation. A summary of the recommended actions in case of active shooting attacks according to this standard is provided below:

1. If someone sees anything that appears suspicious, he/she needs to report it for further assessment.
2. RUN-HIDE-FIGHT (three effective strategies to survive an active shooter): These are not progressive steps. Instead, these are different options that best suit a particular situation and location within the structure during the attack. As one can notice, no single response will fit all active shooter situations, and building occupants must be trained to understand when a response is more appropriate than another.
3. The person must contact law enforcement only when it is safe to do so and never presume that somebody else has already made the call. When the individual encounters officers, he/she must try to remain calm and provide their best commands.

For further information, readers are invited to refer to the following complete guide named "Active shooter how to respond" [32].

2.3. Existing counterterrorism simulators

One challenge to counterterrorism preparedness is the lack of training opportunities. Currently, the common training method for such situations is real-life drills that involve staff, students and first responders that normally include fire, medical and police personnel. This method is complicated to organise, and the costs are often prohibitive in terms of time, money and staff. In order to provide an "improved alternative" in education, whereby costs are kept to a manageable limit without compromising readiness, computer simulations are being used and widely advocated for future training. Although computer simulations cannot substitute real-world experiences, they can simulate real-world environments and replicate objects and characters with a high degree of fidelity in a repeatable manner. Also, this method offers the opportunity for a "risk-free" exercise experience without the undue consequence of property damage or personal harm.

There are a few counterterrorism simulators, and most of them result from research projects. The following subsections provide an overview of the most popular applications, including the EDGE [26], Standoff [25], AUGGMED [27], and the V-Armed [24].

2.3.1. EDGE

The US Army and Homeland Security Department developed a computer-based simulator to train people in a school environment (i.e., teachers and first responders) to react to an active shooting attack. The project is based on a multipurpose Homeland Security simulator named Enhanced Dynamic Geo-Social Environment (EDGE) [26], designed for active shooting attacks that may occur in a school environment. An updated version of this simulator, launched in June 2018, simulates an active shooting scenario in a 26-story hotel that includes various possible scenarios for first responders training: a conference centre, a restaurant, and office spaces.

2.3.2. Active shooter or standoff

Active Shooter [25] is a simulation of an active shooting situation developed by a Russian video game developer (Anton Makarevskiy), where players can choose to be either the shooter or a SWAT team member tasked with neutralising the situation. Its release was scheduled for June 2018 via the Steam game platform. After a controversy accusing the game of promoting gun violence, Valve Corporation [12] removed the publisher from the platform, but the developer still released the game independently. A couple of weeks later, the game was renamed Standoff and published through the Google Play platform. Another version named Standoff Multiplayer was published, offering an online confrontation of terrorists and counter-terrorists in a free multiplayer mode. One can choose a role and weapons in multiple game modes such as Arms Race or Sniper Duel and play online with thousands of players from all over the world.

2.3.3. AUGGMED

AUGGMED [27] is a multi-agent counterterrorism training tool in VR and mixed reality environments with automated simulation. The AUGGMED project aimed to develop a SG platform to enable single and team-based training of end-users with different levels of expertise from different organisations responding to terrorist and organised crime threats. This project has been funded by the European Union's Horizon 2020 research and innovation programme.

The AUGGMED platform is implemented to provide training to prepare and defend against terrorist attacks. It generates adaptive training scenarios and delivers them through different multi-modal interfaces and devices. It also incorporates tools that enable trainers or safety educators to set learning objectives, define custom scenarios, monitor training sessions, intervene in real-time to modify scenarios or provide feedback, as well as evaluate trainees' performance.

2.3.4. V-armed

The V-Armed [24], a team of developers dedicated to creating large-scale VR training, developed a location-based VR tool that simulates several real-life shooter and hostage scenarios. The SG tool was designed to train police officers to subdue a target without endangering the lives of any civilians. The tool can track the progress of participants. The accuracy, the bullet trajectory and the quality of the negotiations can also be retrieved. This technology helped the NYPD (New York Police Department) to train hundreds of officers during a week-long pilot program. The training session took them through various highly realistic active shooter scenarios based on real incidents.

In summary, while the V-Armed SG is very powerful, it is only intended to train police officers and first responders. Similarly, the AUGGMED project is not devoted to preparedness for an educational environment shooting. The Active Shooter (Standoff) could be used for counterterrorism preparedness, but it is not the primary goal of the developer. While the EDGE tool is designed for mass school shooting preparedness, it does not fully immerse the user in a virtual environment. Also, the EDGE tool's effectiveness was not assessed, unlike the present study, which tests the newly developed simulator.

3. VR-based SG prototyping

The following sections describe the decision-making process behind the design of key components of the developed counterterrorism prototype for educational environments. These include the selection of the game engine, the virtual environment, the active shooting simulation, the VR navigation technique, the non-player characters, the storylines and the learning outcomes.

3.1. Game engine

To date, several approaches and hardware/software solutions can be used to develop a VR SG. Several game engines have been used to develop SG tools (or games in general), and the selection among them depends on the type of SG and its features [33,34]. The proposed VR SG was developed using the Unity game engine as it provides a time- and cost-effective option when developing a VR SG. Unity is widely available, with free licences for academic and non-commercial use. Moreover, it is considered the most easily accessible engine, with built-in VR support, extensive tutorial provision and a community network. Unity provides SG developers with great interoperability solutions to import building geometries from BIM models or other 3D formats, as discussed in Refs. [34,35]. Finally, Unity allows environment development using multiple paradigms, including visual coding and traditional scripting. The prototype was developed using C# scripts controlling the user's interaction with the environment throughout the shooting simulation as well as in-game events.

3.2. Virtual environment

For the setup of the virtual environment, this research used a ready-made commercially available 3D model shown in Fig. 1(a) and (b) [36]. This 3D model was in line with the prototyping idea to develop a VR SG for a university environment. For the purposes of this study, participants were informed that this hypothetical building is part of a university campus. This model was imported into the Unity game engine following the process shown in Fig. 1(c). Furniture, such as bookcases and decorations, was added to the original 3D model to increase its fidelity to a university library.

The building consists of 3 floors; however, navigation is allowed only on Floor 1 (i.e., the ground floor) and Floor 2. The top view of these two sections is illustrated in Fig. 2. These two floors are connected through two staircases (Stairs A and B). The model also includes an elevator, which is not used in the training session. Access to the outdoor of the building is possible through two entrances and exits in the main hall on Floor 1.

In real-life buildings, various countermeasures such as access control and safe rooms (or hide locations) are implemented to protect building occupants in case of a shooter attack. In order to incorporate building access control countermeasure, the doors (see Fig. 2) of the building floors were made dynamic and interactive to allow users to access the floors during the normal activity of the building (i.e., before the attack) and block them during the attack. In addition to interactive doors, other game objects such as a cell phone, a computer and drawers were made dynamic to allow the user to interact with those objects and use them to achieve a learning objective during the gameplay. Triggers were also added to the virtual environment to detect if the user reached a specific location or to start a within-game event. Fig. 3 shows a screenshot of a scene with interactive objects.

A final step was to optimise the virtual world through lightmapping generation. Lightmapping is a form of surface caching in which lighting characteristics of surfaces are pre-calculated and stored in texture maps instead of being calculated in real-time. Furthermore, occlusion culling algorithms were used, preventing the rendering of objects outside the participant's field of view and reducing the time it takes to update the screen shown to the participant.

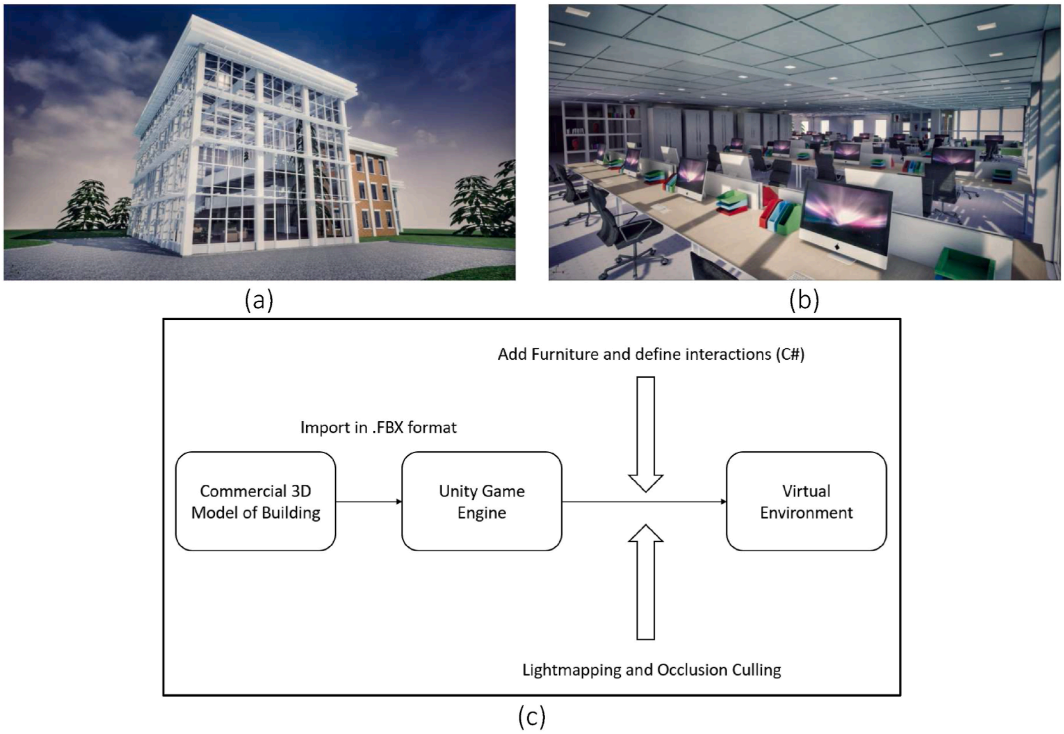

Fig. 1. SHC QUICKOFFICE 3D: (a) screenshot from outdoor; (b) screenshot from indoor area on Floor 1 [36]; (c) workflow for environment creation.

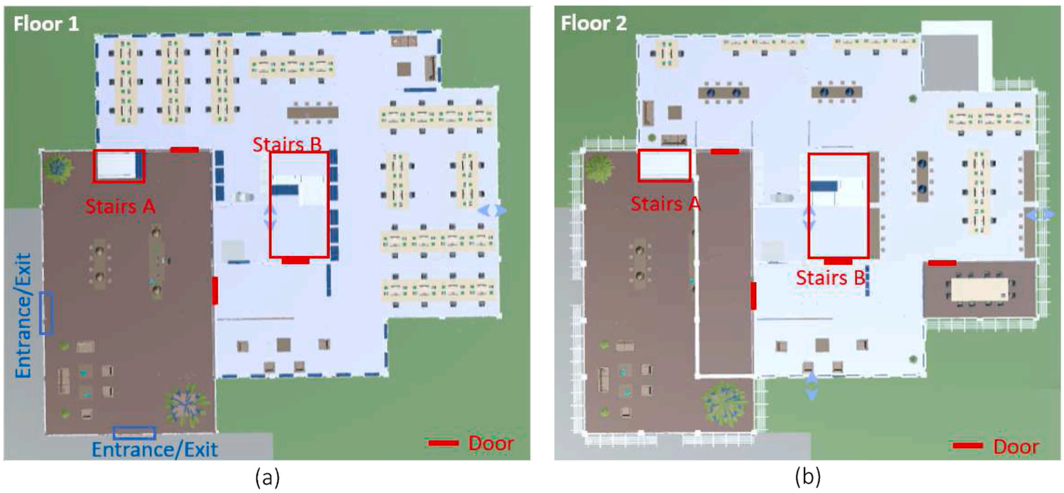

Fig. 2. Top view of (a) Floor 1 and (b) Floor 2.

3.3. *Active shooting simulation*

The active shooting attack was simulated using a non-player character (NPC), as shown in Fig. 4, playing the role of the attacker combined with an audio clip replicating gunshots sound. According to recent statistics [37], most of the past shooting attacks were carried out by male offenders, while data [38] also shows that they often used handguns as weapons. Another recent study [39] shows that young mass shooters are more likely than older. The design of the developed SG took into account these observations; hence the virtual shooter was assumed to be a young male armed with a handgun, as shown in Fig. 4. No blood effects or direct gunshots were employed in this simulation due to ethical and moral considerations. The gunshots audio clip is used as the initiating event of the attack while the shooter moves toward the participant's avatar location (which is dynamic as the participant navigates in the virtual world) in the virtual environment holding a gun.

Fig. 3. Interactive game objects examples (highlighted in red). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Fig. 4. Shooter NPC in the VR SG tool.

3.4. VR navigation technique

There are various existing VR navigation techniques, such as free locomotion and locomotion in place, e.g. continuous movement and teleportation [34,40,41]. Each of these techniques has its own benefits and drawbacks that need to be considered when designing a VR SG. The primary driver for this choice is VR-induced motion sickness, a feeling of nausea that is induced partly due to the user's body being stationary in the physical world while he/she experiences motion in the virtual world. While some solutions are suitable for evacuation experiments to provide a high ecological validity and realism, other navigation solutions provide less realism but can fulfil the training goals of a VR application.

The free locomotion technique is the best approach to prevent motion sickness and promote users' immersion in the virtual environment [42,43]. It requires the users to be able to move freely in the real world while their movements are tracked and transferred to the virtual environment. However, this solution requires a walkable area large enough to accommodate the entire virtual environment and any existing physical elements and obstacles. Therefore, this is not a feasible approach for this study, as the virtual environment is a building with large spaces and multiple floors. In turn, continuous movement techniques often use the VR headset orientation to define the navigation direction, while joystick or touchpad inputs are used to change navigation speed in the virtual environment. In other words, the users can navigate only in the direction they are looking at. As such, this solution requires the user to rotate their whole body during the VR experience, which can be hazardous. Therefore, it was deemed unfit for the purposes of this study.

The last VR navigation technique is teleportation, which allows teleporting the user from one location to another, rather than physically or virtually walking. In effect, the user simply points where he/she wants to be in the virtual environment using one of the VR controllers (see the green pointer in Fig. 5a) to teleport to that location selected by the user instantaneously (see Fig. 5b). This reduces the feeling of self-motion to milliseconds as it does not involve any perceivable translational motion. Motion sickness can considerably impair users' performance in virtual environments [44,45]. Therefore, it is critical to mitigate its incidence in developing user-friendly VR training prototypes. Teleportation was the user navigation technique utilised in this study as it is expected to reduce

Fig. 5. Teleportation technique example: (a) teleportation pointer (green circles) in the virtual environment; (b) user view after teleportation. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

the incidence of motion sickness compared to the continuous movement method, which is known to be very sensitive to motion sickness, affecting approximately 5% of users [34].

3.5. Non-player characters

Non-player characters (NPCs) are avatars not controlled by the SG user. In this research, the NPCs represent the crowd that is supposed to be present in a library building, as shown in Fig. 6. All NPCs except the shooter are non-interactive and located across all building floors. They carry out various independent activities, such as walking, reading a book, talking on the phone (outside the building), typing on a computer keyboard, or standing at the reception during the initial phase of the experience. Before the start of the emergency, the user cannot interact with them, and they move or act according to their assigned animations. After the onset of the aggressor, the NPCs have only two possible behaviours: hide in a pre-defined location decided by the developer or run to the safe zones. These movements of the NPCs are managed by the NavMesh algorithm in Unity. This algorithm creates a navigation mesh that approximates the walkable surfaces in and outside the building allowing the NPCs to move on it to reach their targets, i.e. hide locations or safe zones.

The prototype includes C# scripts that trigger specific animations depending on the situation, the attack scenario, and the movement of the NPCs. As such, these scripts handle the transition from the NPC behaviours before and after the emergency. The pipeline used to create, animate and manipulate the NPCs is similar to the one discussed in Refs. [34,35].

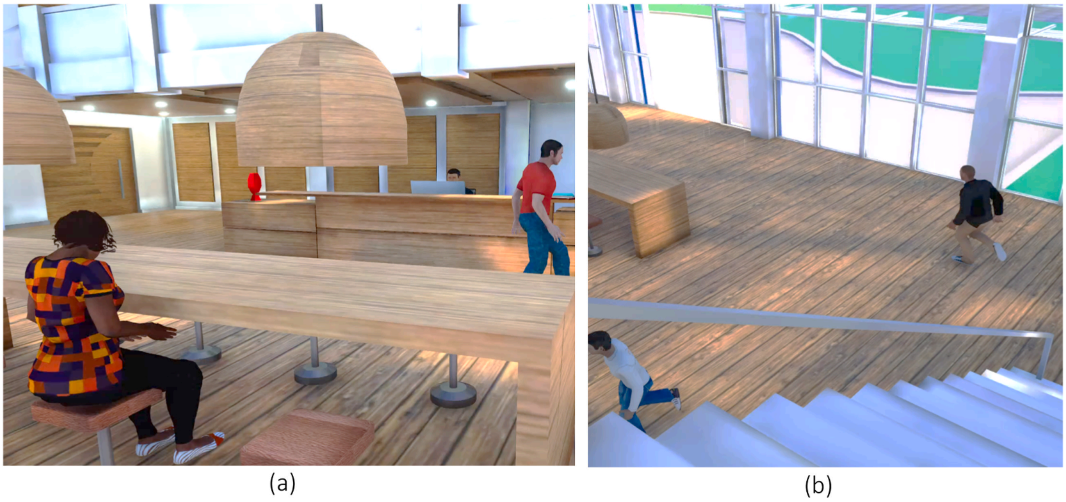

Fig. 6. Examples of NPCs used in the VR SG tool: (a) before and (b) after the shooting attack.

3.6. Learning outcomes and storylines

A procedural simulation was adopted in this research, where the user must follow a sequence of objectives to learn how to respond in case of a shooter attack. The game objectives are derived from the protocol published by the US Department of Education (discussed in section 2.2), which provides a series of learning objectives that should be considered when designing a training program for active shooting attack preparedness. This protocol is mainly designed to train people on the "Run, Hide, Fight" strategy [32].

The standard procedure outlined above highlights three possible scenarios, as follows:

1. The first scenario considers the situation where the threat is far away. In this case, it is recommended to take useful belongings such as a cell phone if possible and exit the building quickly. Once outside, one must find a place to shelter from danger and call for help. This sequence of actions replicates the *run* scenario recommended actions.
2. The second scenario considers the case where it is impossible to leave the building without the aggressor realising it. In this case, it is advisable to hide in a place of safety. For instance, the user can enter a room, close all doors and lock or block them with the nearest heavy furniture, then put her/his phone on silent mode, hide and call for help. This sequence of actions replicates the *hide* scenario recommended actions.
3. The third scenario considers the case where the gunman is nearby. At that stage, it is necessary to prevent her/his progression in any way and escape. Once outside the building, it is recommended to find a shelter from danger and call for help. This sequence of actions replicates the *fight* scenario recommended actions.

In the prototype, the scenarios are presented in the order specified in the "Run, Hide, Fight" strategy, as the intent was to allow the user to explore the two most common actions to take (i.e., running and hiding). Finally, the users experience how to act in extreme situations when running and hiding are no longer options and they need to fight. The rationale was to follow the "Run, Hide, Fight" protocol – according to which the run scenario is the first module to be taught. However, trainees must complete all three scenarios to succeed in the training program. Instruments involve items that measure their knowledge in all three scenarios together. Trainees are not likely to be biased or "primed" by previous scenarios because, in each one, they should perform a series of actions specific to that scenario to achieve the objectives (run/hide/fight) (and they are informed beforehand of that). Therefore, what was learnt in a previous scenario does not help them achieve the objectives in the following one as the actions to be taken are essentially different. Regardless, it should be noted that it does not matter whether a trainee learns from a previous scenario, as the training program necessarily encompasses all three scenarios and instruments are designed to measure the combined learning outcomes.

These three scenarios give users the opportunity to put into practice the main recommendations presented in the protocol discussed in Section 2.2. An additional scenario named "Introduction" was also developed, allowing participants to familiarise themselves with the virtual environment and navigation technique. There was no time limit for the Introduction scenario and no limitation on where the user could explore. The participants were invited to explore the possibilities of the game, such as approaching the automatic doors and interacting with them, collecting objects, etc., at their own pace. This step was fundamental as the participants were supposed to navigate through the entire building during the training and use objects to fight against the shooter as described in the Fight scenario. Once the user was comfortable enough with the environment and controls, she/he would use a menu to move to the start position.

The user begins the "Run" scenario by moving to the second floor and is informed that this scenario aims to reinforce the "Run" guidelines. After the user has moved to the starting point (Fig. 7), and after a predetermined amount of time (5 s), there is an audio cue of gunshots, after which the participant is asked to retrieve their virtual mobile phone (Fig. 7), evacuate the building, move to a highlighted safe area outdoor and call the police.

In the "Hide" scenario, after the gunshot audio cues, the user is asked to control the access to the second floor by closing the dynamic doors and blocking them with a heavy piece of furniture such as a drawer, retrieve his/her virtual mobile phone, locate a secure hiding place, hide in that place and call the police.

In the "Fight" scenario, after the gunshots audio cue, the user is informed that there are interactable objects that he/she can use to throw at the hostile aggressor (Fig. 3). After seeing the aggressor, the user throws these virtual objects at him and evacuates the build-

Fig. 7. The starting point for the emergency on Floor 2 and virtual mobile phone location.

ing. Once outside and hiding in a highlighted safe area, the participant must call the police using the correct phone number (111, in New Zealand).

The VR SG developed in this research is designed to be autonomous so that it does not require any external assistance during the gameplay. Interactions between the game and the participant were designed to be simple, clear and easy to execute; thus, the user is guided by a pre-recorded instructor voice telling what to do, how and when.

4. Evaluation

To evaluate the performance of the VR SG prototype, a user-centred laboratory experiment was carried out with 32 volunteers. Given the scenario under investigation (i.e., a university library), participants were recruited in the Albany campus at Massey University (Auckland, New Zealand) among students and staff. Participants were invited through advertising of the experiment using posters and social media posts. Sections 4.1 and 4.2 provide an overview of the hardware and procedure adopted in the experiment, respectively.

4.1. Hardware

The VR SG prototype was built for use with the HTC Vive Pro system (Taiwan), a commercially available VR system that uses a head-mounted display (HMD) tethered or wirelessly connected to a conventional computer. The display system works at a 90 Hz refresh rate to mitigate motion sickness and delivers a resolution of 1440 × 1600 pixels per eye (2880 × 1600 pixels combined). The HTC Vive Pro system includes two handheld controllers that can be used to interact with the virtual environment and objects. Finally, position tracking of the HMD and controllers is provided by a pair of Base Stations 2.0 (sensors) that can locate these items in the virtual environment with sub-millimetre accuracy at 60 Hz. The stations were installed in the lab following the guidelines provided by HTC [46].

4.2. Experimental procedure

A flowchart summarising the experimental procedure is provided in Fig. 8. The participants started the experiment by reading the information sheet that provided details about the study's purpose and content. They signed a consent form to allow the research team to store and use the collected data for research purposes. To collect data, two questionnaires were designed. A pre-training questionnaire was used before the VR training, and a post-training questionnaire was used afterwards. After having completed the pre-training questionnaire, the participants entered the virtual environment. First, participants familiarised themselves with the virtual world and interaction devices in a tutorial environment (i.e., the Introduction scenario discussed previously). Then, when they felt comfortable to start the VR counterterrorism experience, they were presented with the three scenarios progressing through the Run, Hide and the Fight scenario. During the gameplay, at least one researcher was present to provide help when needed. This researcher would only intervene to provide technical help when there were issues with the VR equipment and ensure the participant's safety. Once the participants had finished the three counterterrorism scenarios, they were asked to complete the post-training questionnaire. They were also allowed to view their statistics, debriefed about the VR experience, and then thanked for their participation in the study.

The pre-training questionnaire included four sections (see Table 1). The first section collected participants' demographics such as gender, age, and ethnicity. The second section assessed their experience with video games, virtual reality technology, active shooting drills, and counterterrorism safety courses. In line with previous studies assessing VR safety training [34,35,47], the third section assessed their self-efficacy and intrinsic motivation levels. Questions in this section adopt a 7-point Likert scale (ranging from −3 to 3). For each respondent, the mean of his/her answers was taken as the grouped score for self-efficacy and intrinsic motivation.

In this work, self-efficacy is defined as "the individual's beliefs about whether he/she is able to perform the recommended coping response" [7]. Such measurement is important as it is a predictor of real-world performance [48]. In turn, intrinsic motivation is defined as the inherent satisfaction associated with the learning per se rather than for some separable consequence of learning [49]. This construct was measured as it acts as a significant predictor of learning through self-efficacy, as shown in the structural equation model by Makransky and Petersen [50].

Combining questions from multiple previous validated instruments is a common procedure in VR studies. The intrinsic motivation items used in this study (Table 1) were adapted from the items used in a recent VR fire safety study by Rahouti et al. [35]. These items were selected from previous studies assessing intrinsic motivation [50,51] and showed good level of internal consistency when used

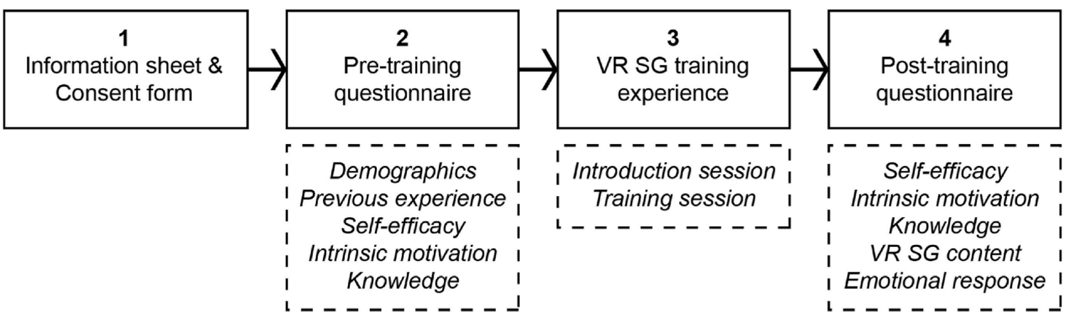

Fig. 8. Experimental procedure flowchart.

Table 1
Pre-training questionnaire structure.

Section	Data type/Metrics	Items
1	Demographics	Age, gender, ethnicity
2	Previous experience	Videogames, VR technology, active shooting drills, counterterrorism safety training
3	Self-efficacy	1. "I am prepared/aware of the correct actions required in an active shooting emergency" 2. "I clearly know the correct actions to take in active shooting emergencies" 3. "I expect to act well in active shooting emergencies"
	Intrinsic motivation	1. "I enjoy counterterrorism active shooting training" 2. "Counterterrorism active shooting training activities are fun to perform" 3. "Counterterrorism active shooting training activities are boring" 4. "Counterterrorism active shooting training does not hold my attention at all" 5. "I would describe counterterrorism active shooting training as very interesting"
4	Knowledge	1. What do you do when you hear shooting? 2. If you want to call emergency services in New Zealand, which number do you use? 3. If during an active shooting emergency, you realise that you forgot your cell phone, what would you do? 4. If during an active shooting emergency, you realise that you forgot your wallet, what would you do? 5. Imagine you are in a room in the building, and you hear a shooting at the entrance, what would you do? 6. Imagine you are in a room in the building, and you hear a shooting in another room, what would you do? 7. Imagine you are in a room in the building, and you hear a shooting in the same room, what would you do? 8. What are the actions to take when you hear shooting in your perimeter? 9. What are the actions to take when the shooting is close to you? 10. What are the actions to take when you hear shooting in a perimeter far from you?

to assess VR safety training. The self-efficacy items used in this study (Table 1) were adapted and rephrased from the original General Self-Efficacy Scale by Schwarzer et al. [52].

The fourth section included a summative assessment of participants' knowledge on how to respond to active shooting emergencies. Participants were asked to answer ten open-ended questions to avoid the suggestion of possible answers that could bias their responses, as highlighted in previous studies [22,53,54]. They were asked to imagine being in a public building such as a library to answer the questions. A knowledge score was given to the participants depending on their answers to Questions 1–10 in Table 1. The answer to each question was coded using the guidelines from the "Run, Hide, Fight" strategy [32]. For Questions 1 and 10, the participants could score between 0 and 3, while for Questions 8 and 9, they could reach a top score of 4. The remaining questions had a maximum score of 1. The final knowledge score was the sum of a participant's scores from the ten questions.

The post-training questionnaire contained the same knowledge, intrinsic motivation and self-efficacy tests as the pre-training questionnaire. This structure allows testing the impact of the VR training approach on the group. However, additional data were collected to assess the VR SG content quality and participants' emotions using the same questionnaire. In line with previous studies [55], the Positive Affect and Negative Affect scale (PANAS) questionnaire was adopted for the emotion assessment. To evaluate the quality of the VR SG content, participants were asked to use the same Likert scale to rate the constructs shown in Table 2. The content quality was assessed using multiple constructs:

1. Recommendations simplicity
2. Recommendations usefulness
3. Engagement
4. Game usability
5. Game realism

The items relating to these constructs were adapted from the questionnaire used by Rahouti et al. [35] to assess their VR safety training application (Refer to the Appendix: Questionnaires Items and Their Source). Finally, two additional items were included to assess whether the participants had any sense of urgency while going through the training and whether they preferred this VR training approach over some traditional training they had experienced.

Table 2
Post-training questionnaire structure.

Section	Data type/Metrics	Items
1	Self-efficacy Intrinsic motivation	Same as in the pre-training questionnaire
2	Knowledge	
3	VR SG content quality	1. Recommendations simplicity 2. Recommendations usefulness 3. Engagement 4. Game usability 5. Game realism 6. Perceived urgency 7. I prefer VR training over traditional training
4	Emotional response	Scared, tense, anxious, uncomfortable, nervous, excited, happy, relaxed, comfortable

5. Results

This section provides the results of the experiment carried out to assess the VR training prototype. Section 5.1 provides the details of the participants. Sections 5.2, 5.3 and 5.4 present the results related to the knowledge, motivation and self-efficacy scores before and after the VR training. Finally, Section 5.5 provides the results of the VR content and emotions assessment.

5.1. Participants

Thirty-two (32) participants (11 females, 21 males), recruited via email and social networks, participated in the study. Participants' age distribution is shown in Fig. 9. Their ages range from 19 to 65 years; however, over 70% are between 20 and 29. This could be for numerous reasons, including that the experiment was run at a university so that a large proportion of participants were students or that young adults are more likely to volunteer for VR experiments as they are likely to be more familiar with and interested in games than older adults.

Fig. 10 reports participants' ethnicity data, video games experience, active shooting drills experience, and counterterrorism safety course experience. From Fig. 10-a, it can be noticed that the largest ethnicity group is Asian, representing 63% of the sample. The next largest ethnicity group is European (19%), followed by Middle Eastern (9%) and New Zealander (3%). Fig. 10-b shows that 50% of the participants were not used to playing video games as they reported playing video games only once a year or less; while 22% play video games at least once a month, 16% play video games at least once a week, and the remaining participants play videos games several days a week (6%) or even every day (6%). Fig. 10-c shows that 72% of the participants claimed that they had never participated in an active shooting drill. 13% of the participants practice active shooting drills once a year, while 3% reported that they had practised active shooting drills over 16 years ago. Another 3% responded that they had participated in an active shooting drill only once in their life, and the remaining participants were unsure about the answer. From Fig. 10-d, it can be noticed that 87% of the participants had never attended counterterrorism safety courses, 7% of them had attended a single course, 3% had attended two, and the remaining 3% were unsure about the answer. Finally, participants reported their previous immersive VR experience, which is not reported in a figure for better readability. 66% of the participants had already experienced immersive VR, 31% claimed they had never experienced it, and the remaining 3% were unsure.

5.2. Knowledge assessment

In this section, the knowledge scores reported by participants before and after experiencing the VR training are analysed. Fig. 11 shows the minimum, maximum, median, mean, and interquartile range (i.e., 25th and 75th percentiles) for knowledge scores data using boxplots. This figure shows an evident increment of knowledge immediately after the VR training. The mean knowledge pre-training score was 6.56 ± 2.40, while the mean post-training score was 12.91 ± 4.22. This suggests that, on average, participants have increased their knowledge score by 6.34.

The Mann-Whitney *U* test was used to assess whether there is any statistical difference between the pre- and post-training knowledge scores. The "knowledge score" was defined as the non-normal variable and the "before" and "after" as the binomial variable. The null hypothesis is defined as follows: "the samples are drawn from the same distribution". In other words, it is assumed that there is no statistical difference between the samples. The *p*-value is less than 0.001, suggesting a strong statistical difference between the pre-

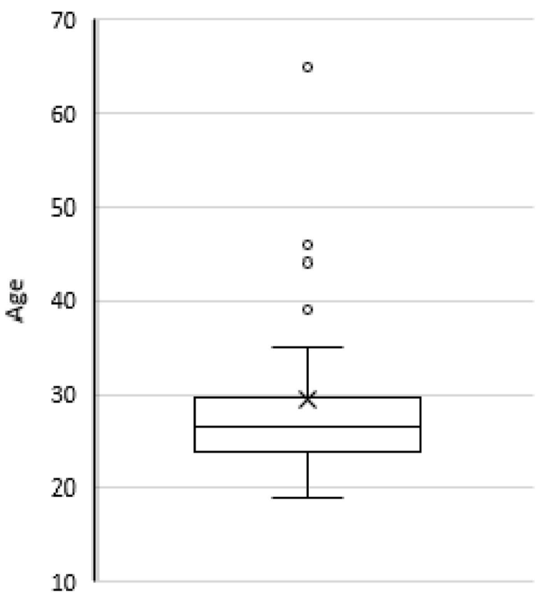

Fig. 9. Participant age distribution.

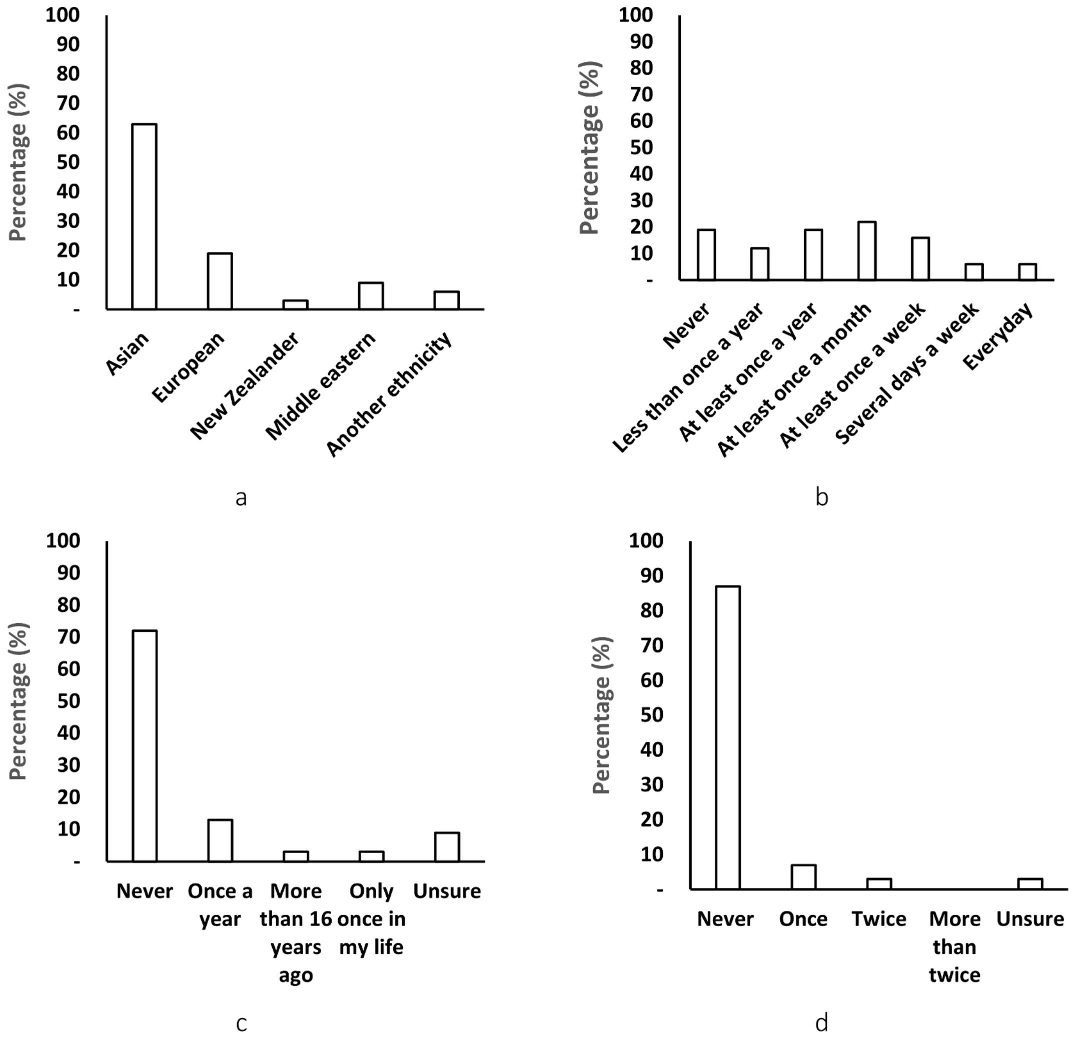

Fig. 10. Participant demographics distributions: (a) ethnic group; (b) video games experience; (c) active shooting past-experience; (d) counterterrorism safety course past-experience.

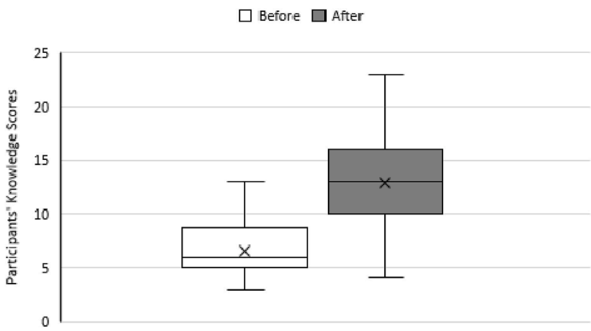

Fig. 11. Participants' average knowledge scores boxplots before and after the experiment.

and post-training knowledge scores. $r = Z/\sqrt{N_{obs}}$ – where Z is the Mann-Whitney U test's Z score and $N_{obs}$is the sample size (or the number of observations) – is equal to 0.99, suggesting a large effect size.

5.3. Intrinsic motivation assessment

In this section, the intrinsic motivation scores reported by participants before and after experiencing the VR training are analysed. Reliability analysis was carried out using the Cronbach alpha statistics. The items show good internal consistency having an alpha of

0.88. Fig. 12 reports the data. As for knowledge scores, there is a noticeable increment of intrinsic motivation immediately after the VR training. The mean intrinsic motivation pre-training score is 0.74 ± 1.06 on a scale ranging from −3 to 3, while the mean post-training score is 1.97 ± 1.04. This suggests that participants increased their intrinsic motivation score by 1.23 on average.

Given that the intrinsic motivation is measured using an ordinal scale from −3 to 3 and that the collected data are not normally distributed, the Mann-Whitney *U* test is again used to assess whether there is any statistical difference between the pre- and post-training self-reported intrinsic motivation scores. The *p*-value is less than 0.001, indicating a strong statistical difference between the pre- and post-training intrinsic motivation scores, while *r* is equal to 0.95, suggesting a large effect size.

5.4. Self-efficacy assessment

In this section, the self-efficacy scores reported by participants before and after experiencing the VR training are analysed. Reliability analysis was carried out using the Cronbach alpha statistics. The items show excellent internal consistency having an alpha of 0.93. Fig. 13 reports the data. As for knowledge and intrinsic motivation scores, there is an evident increment of self-efficacy immediately after the VR training. The mean self-efficacy pre-training score is −0.33 ± 1.44 on a scale ranging from −3 to 3, while the mean post-training score is 1.71 ± 0.79. This suggests that participants increased their self-efficacy score by 2.04 on average.

The Mann-Whitney *U* test is again used to assess whether there is any statistical difference between the pre- and post-training self-reported self-efficacy scores for the same reasons outlined in the previous section. The *p*-value is less than 0.0001, indicating a strong statistical difference between the pre- and post-training self-efficacy scores, while *r* is equal to 0.72, suggesting a large effect size.

5.5. VR experience content and emotions assessment

This section reports respondents' assessment of the VR experience content and emotions felt during the experience. Results of the VR experience content assessment are as follows (on a scale ranging from −3 to 3): (1) recommendations simplicity, mean M = *2.15 ± 0.64* and Cronbach alpha = 0.76, (2) recommendations usefulness, M = *2.16 ± 0.88* and Cronbach alpha = 0.92, (3) engagement, M = *1.12 ± 0.42* and Cronbach alpha = 0.50, (4) game usability, M = *1.74 ± 0.90* and Cronbach alpha = 0.89, (5) game realism, M = *1.65 ± 0.97* and Cronbach alpha = 0.91, (6) perceived urgency, M = *0.19 ± 1.24*, and (7) comparison with conventional training methods, M = *2.03 ± 0.97*. Fig. 14 below shows the data.

Fig. 15 shows the ratings for the items used to assess participants' emotions. According to this figure, participants felt more excited, happy and comfortable during the VR experience than scared, tense, anxious, uncomfortable and nervous.

6. Discussion

This work provides new evidence on how VR SG can be combined to develop counterterrorism training applications for building occupants. As such, this work expands the existing state of the art on the use of VR for counterterrorism training which is today only used by police officers and first responders (see Section 2.3). The developed application is a prototype for the public using educational buildings, where most shooting disasters occurred in recent years (see Section 2.1). The primary goal of this work was to prototype and test a VR SG to enhance the counterterrorism preparedness of the public. This work addresses the prototyping issues and challenges faced in developing the VR SG. Six key components were identified: game engine selection, virtual environment, active shoot-

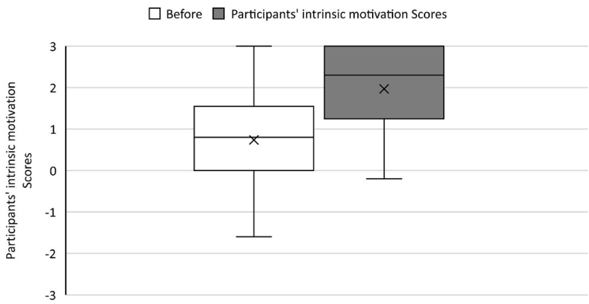

Fig. 12. Participants' average motivation scores boxplots before and after the experiment.

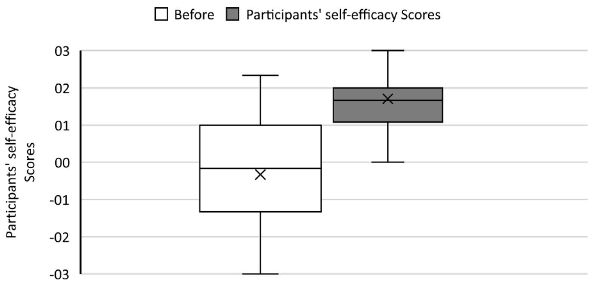

Fig. 13. Participants' average self-efficacy scores boxplots before and after the experiment.

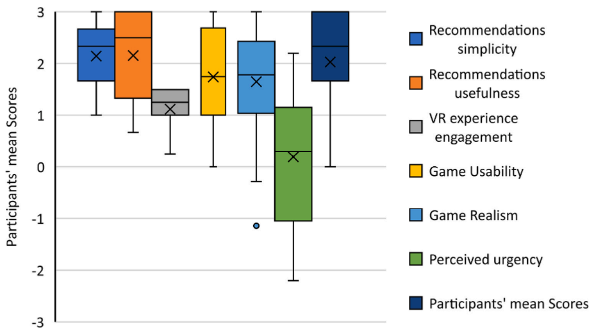

Fig. 14. Participants' boxplots ratings regarding VR experience content.

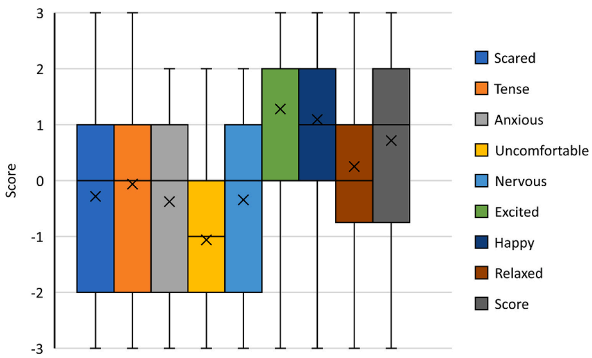

Fig. 15. Participants' boxplots ratings regarding their emotions during the VR experience.

ing simulation, non-player characters, learning outcomes and storyline. The rationales regarding the prototyping choices are discussed in Section 3, providing guidelines for the future development of new VR SG for active shooting preparedness.

The proposed VR SG utilises a 3D model of a hypothetical building downloaded from the internet for the virtual training environment, as described in Section 3.2. This was in line with our goal to develop an application for a broader public to use this application in the future. Also, this approach dramatically reduced the development time and costs. However, it is worth highlighting that future studies should consider developing the virtual environment from existing buildings. This can be done through workflows that take advantage of as-built BIM models of existing buildings or using 3D scanning technologies, as discussed in Ref. [19,33]. Using BIM models might require additional steps in the development stage as it might be necessary to address interoperability issues when importing a model from a BIM platform into a game engine. Moreover, BIM and 3D scanning provide large amounts of data that must be reduced before incorporating into the VR SG to minimise frame rate slowdown. As as-built BIM models are typically heavy files (with many parameters and objects/geometries from other disciplines), their use may require extensive clean-up. As such, using traditional commercially-available 3D models might simplify the process dramatically as these are typically in a file format compatible with game engines and can be optimised to provide a compromise between realism and game performance.

One of the main challenges of this work was prototyping the active shooting scenarios. It was necessary to compromise between the realism of the event and the need to consider ethical and moral issues [34]. Using “too realistic” simulations of shooting events (i.e., representing blood and dead characters) could have triggered strong stressful emotions (i.e., fear and panic) or memories of previous dramatic experiences. This issue was addressed by not incorporating blood and dead characters through the storyline proposed in Section 3.6. The participants' feedback reflects the result of this design choice. Indeed, the perceived urgency in the VR training received a negative score, as shown in Fig. 14. Furthermore, the VR training prototype did not generate negative emotions for most participants, as illustrated in Fig. 15. Negative emotions, for instance, anxiety, may negatively impact learning performance, jeopardising training effectiveness [56]. Therefore, this study did not intend to deliver negative emotions to participants. Moreover, virtual experiences may lead to real consequences. In other words, a virtual experience with intensive negative emotion strongly correlates with negative ruminating in the real world (i.e., harmful thoughts related to distress) [57,58]. Extra care must be taken to mitigate risks and ethical issues in designing active shooting scenarios targeting children and teenagers. Nonetheless, when designing a VR experience to study human behaviour, the need for more stressful scenarios might be required. For instance, a more stressful scenario might be required to investigate the impact of anxiety, stress and negative emotions on building occupants’ decision-making [23]. In short, as stated by Paes et al. [59], the level of realism of a VR experience is application-dependent.

Furthermore, future studies investigating human behaviour in emergencies may adopt other strategies to mitigate the subjectivity of self-reported questionnaire-based measurements of psychological and emotional responses, such as using physiological measures. For instance, changes in heart rate, skin conductance, electroencephalogram (EEG) signals (brain activity), and saccadic eye movement data captured by eye-tracking sensors could be used as objective measures of engagement and stress [60,61]. With sensors integrated into VR HMDs nowadays, using such physiological cues would allow for real-time and accurate data collection [62].

This work also discusses the several solutions that allow users to navigate the virtual environment. The teleportation solution was adopted and tested in this work, as discussed in Section 3.4, mainly due to the need to mitigate VR motion sickness. Given the size of the virtual environment described in Section 3.2, using the free locomotion navigation mode (known as the best solution to reduce motion sickness) was not possible, and locomotion in place was the only feasible option. On top of that, a recent study by Buttusi and Chittaro [41] using the simulator sickness questionnaire [56] indicated that teleportation was the best option in terms of performance, motion sickness, presence, usability, and different aspects of comfort. Indeed, this navigation mode can impact the ecological validity of the behavioural data collected during experiments [55]. However, the goal of the proposed application is only training, and we did not investigate any participants' behaviour. While developing a training tool that mitigates motion sickness represents one of the main obstacles to overtake, teleportation was deemed the best feasible option for this study.

It should be noted that another locomotion option that was not tested in the prototyping is the use of a VR treadmill. These platforms are becoming popular in VR evacuation experiments [23,63,64]. However, recent studies [65] show that treadmills have the limitation of not allowing participants to have natural walking conditions. Moreover, their high costs and low transportability would dramatically decrease the portability of VR training setups, such as the one proposed in this research. As such, this work tested the teleportation solution. In line with the design expectation, none of the participants felt any dizziness during the training. Further, the results of the experiments show that the participants provided a relatively high score for the game usability and realism, as illustrated in Fig. 14.

6.1. Research contribution

To the best of the authors' knowledge, this study is the first attempt to investigate the effectiveness of a VR SG for active shooting emergency training in terms of knowledge acquisition. The results show that participants had little knowledge about the recommended actions in active shooting attacks before the training. Exposure to VR training significantly increased participants' knowledge immediately after the experiment. These findings indicate that using VR to enhance counterterrorism preparedness is a valuable method for delivering effective training. The post-training knowledge scores might be increased further through repeated training sessions using the same application. Similar trends have been observed in previous studies [7,66–69]. Moreover, the analysis also revealed a statistically significant increase in participants' intrinsic motivation and self-efficacy immediately after the training. In other words, the application made the participants more confident in their skills and capabilities to adequately respond to future shooting emergencies. This is in line with the theoretical framework by Bandura [70], which explains how different sources of information provided to people impact their increase of self-efficacy. Further, the increment of self-efficacy could also be justified by the fact that most participants have never undertaken active shooting training before. As such, their starting self-efficacy was relatively low before the VR training. Further, the motivation results indicate that VR is a valuable option to motivate people to attend counterterrorism safety training sessions. This result is in line with previous ones observed for non-immersive VR fire safety training experiments by Ali et al. [71] and Rahouti et al. [35].

From a pedagogical perspective, most participants reported that the simulator provided simple and useful recommendations that facilitated knowledge transmission. They also reported that the simulation was engaging. In effect, some participants reported that they even lost track of time during the VR experience, which suggests a high level of immersion. A highly immersive learning environment strongly affects memory, enabling participants to intuitively recall their experience in the virtual learning environment [20]. Similar results have been reported in the literature that VR training delivers longer knowledge retention than traditional training [72]. These results align with previous studies confirming that VR training can overcome the pedagogical limitations of traditional safety training [73–75].

6.2. Limitations

The first limitation of this study is that it did not assess participants' retention of the acquired knowledge after a certain period (i.e., long-term effect). The proposed application was assessed in terms of changes in knowledge acquisition, self-efficacy and intrinsic motivation before and after the training. However, future studies can expand this assessment by also including a transfer test. Furthermore, this study did not compare the effectiveness of the developed training method (i.e., through a VR simulation) to conventional training ones such as non-interactive videos or slide-based lectures. As such, this study represents an explorative pilot study on the steps required to develop an active shooting training tool for the public. Future studies are still required to establish the effectiveness of the proposed VR training solution against traditional training methods for counterterrorism preparedness. For instance, a reliable comparison could be achieved through a between-subject experimental design with two conditions: the control group receives training through traditional methods (e.g., slide or video presentations) and the treatment group through the VR SG prototype. This comparison method has been adopted in previous studies showing promising results of VR training [22,35]. Another limitation is related to the baseline measurement of intrinsic motivation as participants who had never undergone active shooting training before testing our prototype might have been challenged by rating statements such as "Counterterrorism active shooting training activities are fun to perform". However, none of the participants openly reported such an issue.

In this study, participants' demographics were collected to characterise the sample and ensure it was representative of the study population. Upon analysis (Section 5.1), the sample was deemed a good representative of the training target population (i.e., university students and staff), and findings suggest that the VR SG prototype is efficient for that population. The sample size was determined in this study to allow within-group comparisons before and after the VR training. In line with previous studies in the field [21,76–79], a sample size greater than 30 participants was the target for this study. The sample of 32 participants allowed for detecting statistical differences in knowledge gain, self-efficacy and motivation. However, the sample did not allow for investigating the impact of different participant demographics on the performance metrics. Future studies focusing on the impact of demographics on the training outcomes will require larger sample sizes, more suitable with regression analysis. It should be noted that the VR training prototype should be efficient for a specific but inherently diverse population.

This work only provides a case study for a hypothetical building using an available 3D model of a library. The study shows the feasibility of developing a VR counterterrorism serious game for active shooting in three scenarios. The scenarios implemented in the proposed application were relatively simple, providing users with entry-level information. Further, the storyline was relatively short to avoid VR fatigue for the users. Future studies are required to apply the proposed solution for existing buildings using the building information model of the select building using workflows described in previous literature [34,35]. NPCs in the proposed application do not interact with the users during and after the emergency. Future development could be done to set up pre-defined or AI-based interactions. Indeed, NPCs can play a more central role in the game, instructing users on the actions to take in the three scenarios. Future studies are also needed to investigate the impact of the use of NPCs on the overall training.

7. Conclusion

The main purpose of this research paper was to develop and test an immersive VR SG counterterrorism training prototype to enhance occupants' knowledge in educational environments such as universities about the recommended actions to be taken in such an emergency. The results show that the VR prototype significantly increased the knowledge of the 32 participants who tested the training solution. Further, the results show a significant increment of self-efficacy and intrinsic motivation. The results also suggest that the use of teleportation for navigating in the virtual environment had positive feedback in terms of usability and did not seem to affect the perception of realism. Finally, the developed prototype fulfils the pedagogical objectives of the safety training by providing simple and useful recommendations.

Declaration of competing interest

The authors declare that they have no conflict of interest with this research.

Data availability

The authors do not have permission to share data.

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