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Article *in* Fire Technology · January 2021

DOI: 10.1007/s10694-021-01098-x

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Published as: *Rahouti et al.*, 2021, Prototyping and Validating a Non-Immersive Virtual Reality Serious Game for Healthcare Fire Safety Training, *Fire Technology*

Prototyping and Validating a Non-Immersive Virtual Reality Serious Game for Healthcare Fire Safety Training

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Abstract

In a healthcare context, the success of a fire safety procedure in a real-life emergency mainly depends on staff decisions and actions. One of the factors influencing staff decision-making is their training. In most healthcare facilities, safety educators use slide-based lectures as a training tool. Virtual Reality (VR) is gaining fire safety community attention for being an interesting training tool. However, few studies have assessed the effectiveness of VR-based fire safety training simulators compared with a slide-based lecture. The present research proposes a novel non-immersive VR-based training for healthcare fire safety education. This paper describes the prototyping steps required to develop a non-immersive VR serious game (SG) to train the staff of Vincent Van Gogh (VVG) hospital in Belgium.

The paper finally validates the VR SG comparing its effectiveness against slide-based lecture training. 78 staff from VVG hospital in Belgium participated in this study. They were divided into two groups: Group A was trained using a slide-based lecture, and Group B was trained using the VR SG. The results indicated that the VR SG was more effective than the slide-based lecture in terms of knowledge acquisition and retention and in terms of self-efficacy increment in short and long terms than the slide-based lecture.

Keywords – Virtual Reality, Hospital, Fire Safety, Knowledge, Self-efficacy, Intrinsic Motivation.

1 Introduction

In 2011-2015, United States fire departments responded to an estimated average of 5,750 structure fires in healthcare facilities per year [1]. These fires accounted for 0.1% of the 2,700 civilian structure fire deaths, 1.1% of the 14,167 civilian structure fire injuries, and 0.5% of the $9.8 billion in direct property loss [1]. In 2013, the Belgian fire and rescue services attended over 22,733 declared fires including 236 in retirement homes and 79 in hospitals [2]. These statistics highlight that even though today's healthcare facilities are designed to be *fireproof*, they are still prone to fire events worldwide. To keep fires under control or prevent them from happening, proper staff actions play an important role. Training the staff on fire safety rules is, thus, paramount. All healthcare facilities should have well-defined fire safety procedures and make sure all staff are familiar with them. Staff should know where the safe places (including assembly points, refuge areas, etc.) are, so that they can safely evacuate the hazardous area in the event of a fire. They must also be informed about the extinguishing materials that are available at their workplace as well as their locations and be trained on their manipulation steps. Moreover, there are aspects related to the patients' and visitors' safety. Indeed, staff must look after patients and visitors during fire emergency events. Triage procedures should be, then, also taught to the staff in order for them to be able to ensure the safety of people under their responsibility.

In healthcare facilities, fire safety educators use various training methods to teach the staff fire safety recommendations and procedures [3]. Among those methods, slide-based lectures, seminars, printed documents, videos, and fire drills are the most used [3]. These conventional training methods have different level of trainees' engagement. Fire drills allow trainees to be engaged in different practical tasks and test different safety procedures [4], [5], and [6]. However, drills are mainly organised in outpatients' areas for patients' security purposes (see [7] and [8]) or they are carried out in different environments than healthcare facilities with dummies patients (see [9]). Despite their advantages in terms of organisation and cost-effectiveness as claimed in previous studies such as [5], [6], [10], and [11], conventional approaches present many limitations regarding fire safety education, but also in terms of trainees' motivation and self-efficacy regarding fire safety training.

Fire safety educators are currently experiencing the use of technologies such as serious games (SGs) and virtual reality (VR) to teach fire safety skills ([12], [13]); however, the added pedagogical value of this training method is still not well understood in a healthcare setting. On the one hand, a SG can be defined as a game in which education is the main goal, rather than entertainment [11]. On the other hand, VR can be defined as a computer-mediated simulation that is three-dimensional, multisensory, and interactive, so that the user's experience is "as if" inhabiting and acting within an external environment [13]. VR SGs can be classified as being non-immersive or immersive. Non-immersive VR SGs use a flat screen (e.g. a computer screen) to expose the user to a virtual world (VW), while immersive VR SGs use head-mounted displays to transport the wearer in the VW. Previous studies have investigated the impact of different VR SGs with different levels of immersion on the results. For example, as discussed elsewhere [14], the level of immersion affects the way people perceive the affordances of the evacuation systems under investigation in a VW. In addition, the user's field of view is likely to be limited when using a flat-screen as compared to a head-mounted display solution, but this limitation can be counterbalanced by the cost-effectiveness of this solution as it does not need from the developer(s) to purchase a VR system. In addition, the participants in the present study were stationary (i.e. sitting in a chair); therefore, it is assumed that the field of view will not greatly influence the results. The focus of the present study is thus on non-immersive VR and its comparison with a fire safety lecture slideshow. For easy reading, in the remainder of this paper, it would be referred to non-immersive VR as 'VR'.

VR-based training solutions offer a wide range of possibilities compared to slideshows. They have the advantage of presenting knowledge in a setting similar to real-life scenarios even if they are still presenting many limitations for training tasks that require a physical action. They also provide access to learning materials in a time and place convenient for the learner, and provide interactive feedback critical for self-assessment [12]. Therefore, presenting the same content taught using slideshows through VR could possibly attract more attention and prepare people in a more clear and informal way.

The use of VR in different safety disciplines is on the rise [13]. This increase is not unfounded as several meta-analyses (such as [3] and [15]) reported positive educational outcomes when using VR as a training solution, often exceeding the outcomes associated with slideshows, especially for tasks linked to memory (e.g., wayfinding) or procedure learning (e.g., what actions are required to be taken during a real-life fire). For example, Din & Gibson [15] assessed the pedagogical value of three interventions - a computer-based SG, a paper-based SG (i.e. the paper version of the SG) and a slide-based lecture – to teach safety procedures at construction workplaces. The results of this study showed that the VR SG was more effective than the paper-based one and the slideshow in terms of learning. Another study by All *et al.* [3] assessed the effectiveness of a VR SG for fire safety training and a slide-based lecture in a healthcare context. As such, VR SGs represent an invaluable tool to enhance the effectiveness of fire safety training. However, applications of these technologies for healthcare fire safety training are still rare and have not been properly validated.

This paper focuses on the prototyping and validation of a novel VR SG for healthcare fire safety training. The paper describes the key components required to develop this prototype, i.e., virtual building, users' navigation and interaction with virtual objects, non-playable characters, fire and smoke modeling, storyline, and learning outcomes. The proposed SG was customized to train staff of VVG hospital in Belgium. Finally, this paper proposes a validation study of the proposed prototype by comparing it with slide-based training in terms of trainees' knowledge acquisition and retention, intrinsic motivation and self-efficacy.

2 Literature review

Before discussing the existing studies, brief definitions for intrinsic motivation and self-efficacy should be provided. Intrinsic motivation is defined as the performance of an activity for the inherent satisfaction with the activity itself, rather than for some separable consequences [16]; while self-efficacy is defined as participant's perceived capabilities for learning or performing actions [17].

There is an increasing interest in studying the real outcome of VR SGs in terms of training and behavior assessment. Many studies praised the educational value of VR in different safety disciplines, including earthquakes (e.g. [18]), terror attacks (e.g. [19]), as well as fires (e.g. [20], [21], and [22]) and aircraft emergencies (e.g. [10], [23], [24], [25], and [26]). A comprehensive review of VR SGs for safety education was proposed by Feng *et al.* [27]. However, this study focused on safety in general, unlike the objective of the current study. Indeed, this section provides a review of existing studies on the use of VR as an educational tool to improve trainees' safety skills and their attitudes, such as intrinsic motivation and self-efficacy.

Shu *et al.* [18] investigated the effect of VR on trainees' earthquake preparedness and task-oriented self-efficacy, among other variables, when exposed to a life-like earthquake scenario. The results showed statistically significant differences between the pre and post-tests measurements of participants' earthquake preparedness and self-efficacy. Similarly, Chittaro & Sioni [19] compared an interactive and passive version of a SG that simulated a terror attack scenario in terms of participants' knowledge and self-efficacy. The results showed a significant increment in counterterrorism preparedness and self-efficacy with either training method. The increment of users' knowledge and their self-efficacy immediately after the training, as reported in the above-discussed studies, demonstrate the promise of using VR for safety training. However, both studies (i.e. Shu *et al.* [18] and Chittaro & Buttussi [10] did not evaluate the long-term effect of the developed VR SGs on participants' knowledge and self-efficacy and did not compare these SGs with slideshows.

Tate *et al.* [20] argued that training shipboard firefighting procedures through VR is more effective than the standard training methods used by firefighters. Smith & Ericson [21] proposed a VR SG for teaching best practices and escape techniques when facing fire hazards. This study focused on participants' knowledge gain and change in motivation after being exposed to the virtual simulation. Results of this study highlighted the improvement in participants' motivation for fire safety training, while no short-term knowledge gain was observed. Similarly, All *et al.* [3] assessed the short-term effect of fire safety training by comparing a VR SG and a slide-based lecture in terms of knowledge and intrinsic motivation. With respect to the slide-based training method, the results showed that the VR SG was more effective in terms of knowledge gain and motivation enhancement. Although this study provided evidence regarding the short-term effect of VR SG and slide-based training solutions, the authors have suggested the investigation of the long-term effect of either intervention. This will be addressed in the present study by assessing participants' self-efficacy, the long-term effect of either training on learning and the content of the proposed VR SG in addition to the short-term effect on knowledge and intrinsic motivation investigation. Lovreglio *et al.* [22] compared fire extinguisher training using VR with a non-interactive training video in terms of knowledge acquisition, retention of information, and change in self-efficacy. The results revealed that the VR trainees scored better than the video trainees in terms of knowledge acquisition immediately after the training. The same trend was observed for long-term retention of information. In addition, a higher increment of self-efficacy was observed right after the training. The VR trainees maintained the same level of self-efficacy even three to four weeks after the training, whereas the video group had shown a significant drop of self-efficacy after this period. Overall, in addition to the positive increment of knowledge, the three above-discussed studies demonstrated the importance of using VR SGs to motivate people to attend fire safety training sessions that are often considered as tedious by the staff.

Chittaro & Buttussi [10] assessed the effectiveness of a VR SG for aviation safety training and compared this training method with the well-known safety card. The results highlighted that the VR SG was more effective than the safety card in terms of knowledge transmission and retention. Another study by Burigat & Chittaro [123] in the same safety area (i.e., aviation) investigated the effectiveness of a VR-based training tool in terms of spatial knowledge acquisition and compared this tool with a printed diagrammatic map. Results of this study revealed that the VR SG produced better spatial knowledge when participants were asked to pinpoint their assigned position in the environment. Chittaro [24] compared the effectiveness of three aviation safety briefing interventions - i.e., safety briefing cards, safety briefing videos and a safety briefing video extended with basic interactive controls (this can be assimilated to a VR SG). The results showed that the two video solutions were more effective than the card solution for aviation safety briefings. In the same vein, Chittaro *et al.* [25] explored how safety recommendations administered on smartphones were able to improve aviation safety education. The results showed that users who were trained through this medium were able to transfer the presented knowledge to the real world and don an aviation life preserver faster and with fewer errors compared with those who used briefing cards. Moreover, participants who used the VR SG reached a higher level of self-efficacy. Finally, Chittaro & Buttussi [26] explored the use of arcade games for aviation safety training. They focused on participants' knowledge increase and change in self-efficacy. The results revealed that the game was more effective to improve users' self-efficacy and knowledge than briefing cards.

In summary, previous research studies have shown that VR SGs were effective safety training tools. Some studies have highlighted that VR SGs can be even more effective than the slideshows and briefing cards (in the case of aviation) in terms of knowledge gain and participants changes in attitudes, especially for tasks that do not require a physical action from the user. However, those studies focused separately on those variables. Some studies focused only on short-term knowledge gain. Others focused only on participants' change in motivation, while the remaining focused on participants' change in self-efficacy. Only All *et al.*'s study [3] was run in a healthcare context and was limited to the short-term effect on trainees' knowledge and motivation.

3 Materials and Methods

The authors developed and validated a non-immersive VR SG for fire safety training in order to assess the effectiveness of this training approach against slide-based training. The components required to prototype the new VR SG are described in Section 3.1, while the validation procedure is described in Section 3.2.

3.1 VR SG Prototype

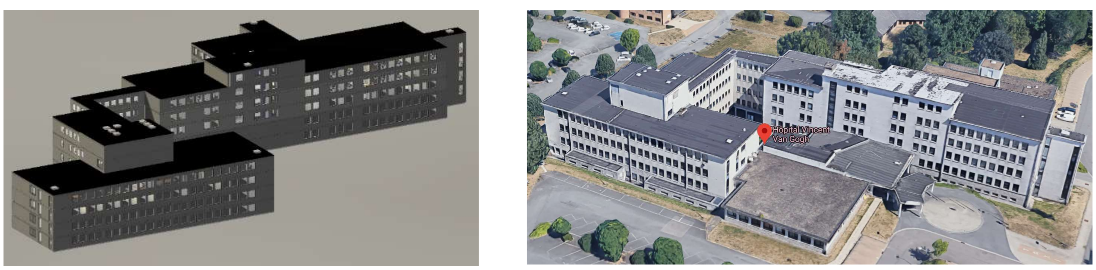
SG developers have the possibility to choose among several game engines to develop their training tools. To date, there are hundreds of commercial and open-source game engines that can help developers with their developing needs [40]. The non-immersive VR SG, proposed in this work, was developed with Unity 5 game engine (https://unity.com), which is one of the most popular engines used for the development of SGs [11]. We decided to select Unity as it offers a wide range of features that can be included in the world of play and has useful supported libraries and programming languages, among other advantages. For instance, most of the scripts used in the development of the VR SG described below are written using C# programming language.

The SG was customized to train the staff of the VVG hospital in Belgium. This specific case study was selected as the safety educators of this hospital expressed the need for alternative solutions to train their staff on fire safety rules as the adopted training solution that combines slide-based lectures and hands-on training on firefighting equipment showed weaknesses in terms of intrinsic motivation, knowledge transmission and long-term retention of information.

The following sub-sections (i.e., 3.1.1-3.1.5) describe the key components of this tool.

3.1.1 Virtual building

The virtual building (see Fig. **1**-a) is a replica of the main building of VVG hospital (see Fig. **1**-b) located at Marchienne-au-Pont, in Belgium. This building is a 6-story structure (i.e., R-1 to R+4) as shown in Fig. **1**. It is the acute psychiatric structure of Charleroi hospital and its full capacity is 270 beds.



a b

Fig. 1 Virtual (a) and actual (b) buildings. Photograph "b" was taken from Google Maps.

Different modeling techniques exist to create the 3D geometry of a building, including Building Information Modelling (BIM), laser scanning, etc. In order to create the 3D model of VVG hospital, we have adopted the BIM modeling technique. The workflow followed to create and import the BIM model in Unity is shown in Fig. **2**. The BIM tools used in this research to create the BIM model are Autodesk products (i.e., Revit and 3DS Max).

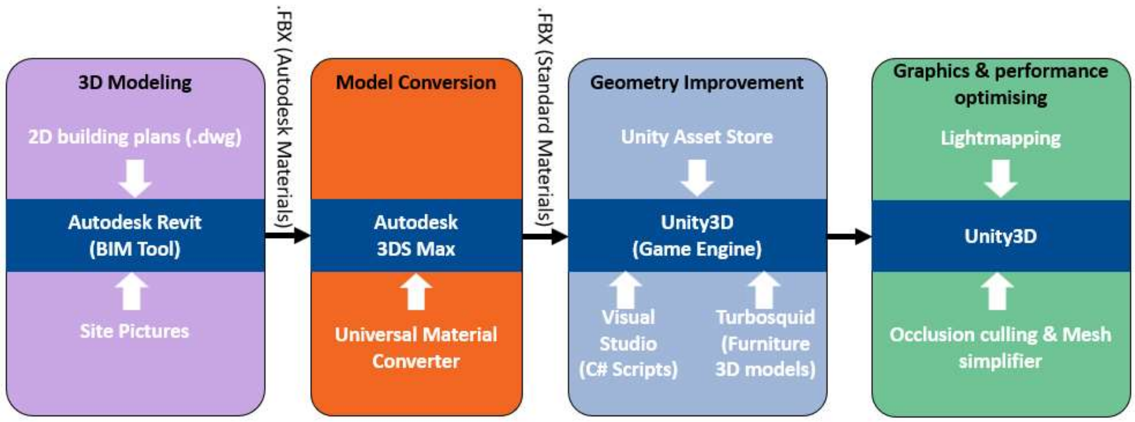


Fig. 2 The workflow followed to create the BIM model using Revit and 3DS Max software and to import the model in Unity

As shown in Fig. **2**, to replicate the selected building components, including rooms, doors, windows, stairs, other building components, we used the CAD plans of all floors as input data. In addition, during inspections, elements in the actual building that would act as audio and visual cues to people during a fire emergency were identified, and their locations confirmed or added to the plans (if this was missing in the original documents) so that they could be accurately included in the final version of the 3D model. These included lights and light fittings, fire alarm triggers, fire alarm sirens, emergency signage, and fire extinguishing equipment.

Site photographs were taken to aid in locating furniture and texturing the 3D model. Once this data was available, the building was replicated and imported in Unity where geometry was improved. For instance, some of the objects were not available in the original Revit libraries. Thus, they were added to the 3D model from the asset store of Unity to make the virtual building more accurate to the actual one and increase its realism. Chairs, beds, medical furniture, shelves, computers, paper boxes, plants, among other furniture, were placed in appropriate locations. Fig. **3** shows an example of an office located on the third floor without and with added furniture. Interaction with furniture would be detailed in Section 3.1.2.

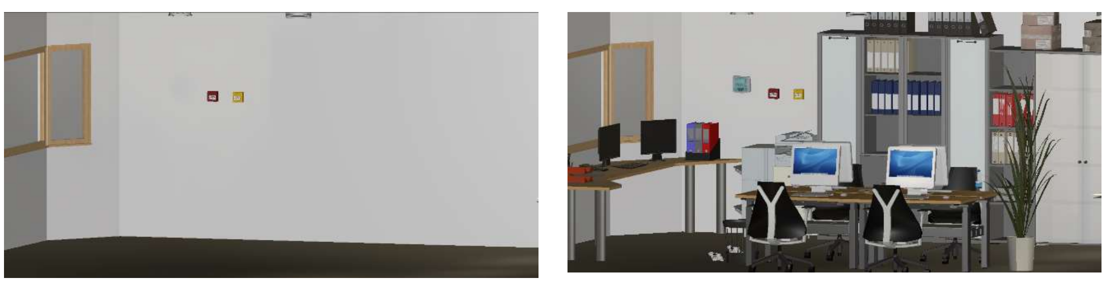


Fig. 3 Example of unfurnished (left) and furnished (right) office

Although all storeys were modelled, only the third floor, where the psychogeriatric unit is located, was used for the development of the storyline discussed in Section 3.1.5.

3.1.2 Navigation solution and interaction with the virtual objects

To set up the navigation solution, developers must define the camera location (representing the user view within the game) and the virtual body translation technique. Two approaches - i.e., first-person perspective (FPP) and third-person perspective (TPP) - can be used to define the camera location. For instance, using FPP, the user can see through the virtual character's eyes, while, using TPP, the user plays as the avatar, but a camera view is always behind the virtual body of the user. In this research, we adopted the FPP to enhance the sense of embodiment toward the user's virtual body. Previous studies, such as [38], have provided evidence in favor of FPP against TPP, confirming the relevance of using FPP to induce a sense of embodiment toward a virtual body, especially in terms of self-location and ownership. In the development of the VR SG, the standard first-person controller (FPC) of Unity was used. It allows the control of the in-game user's viewpoint via the mouse, but it also controls the translation of the user's virtual body via the keyboard arrows (i.e. up, down, left, and right).

Interaction with the 3D virtual objects (VOs) within the virtual building is one of the common challenges for the development of VR SGs. Interaction means with the VOs such as doors, chairs, alarm triggers, fire extinguishers, and so on, depends on the immersive nature of the VR application. For instance, in non-immersive VR applications, traditional game controllers such as the combination of the mouse and keyboard, or PlayStation controller, or Xbox controller, are always used as input devices to interact with the VOs. The developed prototype allows interaction with the VOs via the mouse and keyboard.

The typical tasks performed are object selection and manipulation. Object selection is performed by positioning the mouse cursor over the object and pressing the right button of the mouse. This is based on ray casting technique available in Unity via the physics engine. It casts a ray from the camera origin through the pixel selected via the mouse pointer to find the first intersection point with a collider in the scene (see **Fig.** ***4***). This information can then be combined with the object's name or its tag in order to identify it. Object manipulation consists of two fundamental tasks: object translation and rotation. For example, the manipulation of a selected wheelchair consists of translating it to a specific position and rotating it to match with a specific rotation. The mouse is used as an input device to position selected objects in the virtual building. The example of the wheelchair was only taken for illustration. Many VOs were made interactive to allow trainees to grab/drop them, using them (such as fire extinguishers to attempt putting out the fire), transporting them to a specific location, etc. All scripts and methods for interaction with the VOs were developed from scratch.

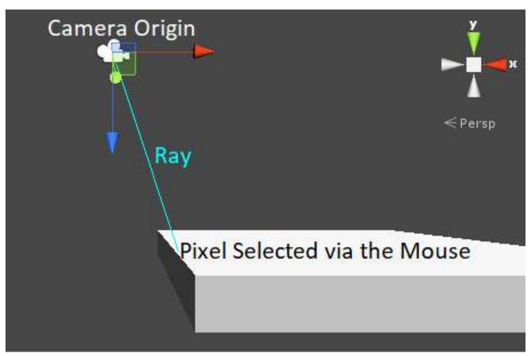


Fig. 4 Ray casting technique concept

3.1.3 Non-playable characters

Non-playable characters (NPCs) are any character in a game that is not controlled by the player. Instead, they are controlled by the computer via algorithmic, predetermined, or responsive behaviors. In this research, NPCs are used to populate the virtual building and play the role of a typical hospital population, including caretaking staff, patients and visitors. We designed two categories of NPCs: non-interactive and interactive NPCs. Non-interactive NPCs play passive roles during the simulation. For example, some of them are in corridors where they have pre-assigned tasks at the beginning of the scenario. They display a daily routine behavior such as talking with another NPC, eating/drinking something, wondering in hospital areas, etc., but they can also display emergency behaviors such as evacuating towards a place of safety. Conversely, interactive NPCs are used to play an active role during the scenario. For example, they may guide, help or accompany the trainee to perform a task.

A workflow was developed in [11] to create NPCs and animate them using a series of software packages, as illustrated in Fig. **5**. The same workflow was used in the present research study. The NPCs were first created in Adobe Fuse CC (https://www.adobe.com/be_fr/products/fuse.html) (FS icon in Fig. **5**), which is a software for creating 3D human characters. Then, the models were uploaded to Adobe Mixamo (https://www.mixamo.com) for skeleton rigging and animating. Mixamo is a 3D character cloud-based animation library that contains several animations, allowing rapid animation development. After rigging and animating, the characters were exported in an FBX format and then imported to Unity. Where the desired animations were unavailable in the Mixamo library, they were created from scratch using the animation window of Unity or UMotion Pro package (from the Unity Asset Store).

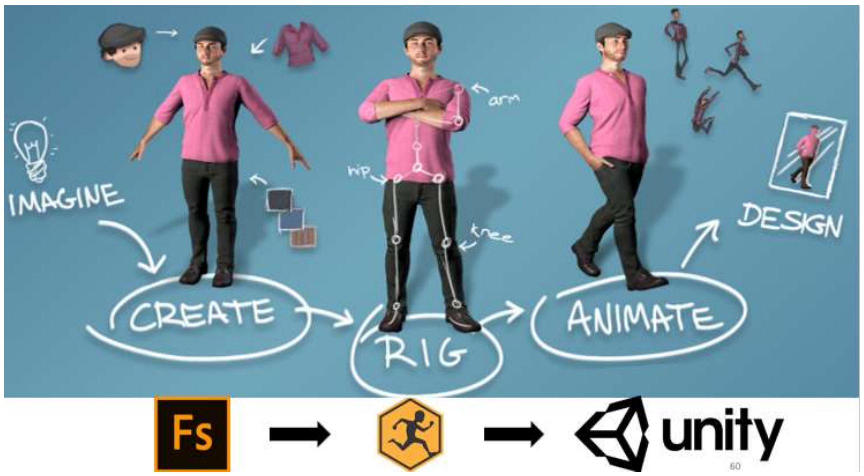


Fig. 5 NPCs creation, rigging and animating workflow. This figure was modified from the original figure in [39]

To make NPCs more realistic, a plugin named Salsa with Random Eyes was used to create facial expressions. As such, the NPCs lips moved when they were speaking and blinked like real human beings. In addition, to make an NPC's head points in the direction of the player when interacting with him/her, Headlook Controller package scripts were used. Furthermore, NPCs were assigned tasks where necessary. The non-interactive NPCs speak during the game without interacting with the player, while the interactive NPCs speak whenever events are triggered by the player (e.g., entering a room, taking action, being close to an interactable NPC, etc.). The final step was to control the NPCs' animations, including non-interactive and interactive animations. This step is done within Unity itself. Changes between the animations are controlled by transitions. The transitions between animations are handled via C# scripts. Animations were triggered under certain conditions so that they became active in the game. The dialogues were created by using free Text to Speech software available on the web such as TTS (http://www.fromtexttospeech.com/) or ttsmp3 (https://ttsmp3.com/).

NPCs navigation is based on A* algorithm, which is embedded in Unity, while their behaviors are controlled via a newly developed algorithm. It controls their actions in normal (i.e., before the fire emergency is announced) and in an emergency. Basically, this algorithm allows replicating a set of daily routine actions usually observed during normal activities such as finishing a phone call, eating, typing on a keyboard, wondering in the corridor, speaking with others, and specific ones such as providing/receiving care, among others. On the other hand, it also allows performing emergency actions including, firefighting, rescuing others, containing a fire, searching relatives, waiting for an order, giving an order, checking the situation, gathering belongings before leaving the hazardous area, evacuating, selecting an emergency exit or an evacuation path, following another NPC or the player (seen as a leader) during the evacuation, staying inside the building (or compartment) regardless of the alarm signal, etc. All those behaviors are implemented using C# programming language. The transition from one behavior to another depends on the situation and on various attributes of the simulated NPC. For instance, in normal situations, a staff member will perform a daily routine activities such as talking with a colleague.

Then, if the alert is triggered, s/he will perform an emergency action such as checking the situation or attempting to extinguish the fire.

3.1.4 Fire and smoke modeling

The fire event represents a key component of the fire safety training simulator and must be represented in the virtual scene. There are two methods to represent fire, and smoke spread in game engines: qualitative or quantitative. The qualitative method consists of using the particle systems of the game engine to generate fire and smoke effects, while the quantitative method consists of simulating the physical spread of fire and smoke based on laws of physics and fluids dynamics within the game engine itself or using a third-party CFD software and then importing the data into the game engine [41]. In this research, we used the qualitative method in order to simulate the fire and smoke because calculating or importing the physical spread of smoke and fire is very challenging due to numerous reasons. For instance, if we assume that the approach adopted is to import pre-calculated simulations from third-party software, the first challenge lies in the fact that this process cannot be done in real-time due to the large volume of output data generated for a single simulation. This is highly linked to the complexity of the geometry and its dimensions, but broadly spoken, it can represent a few Gigabytes of data per simulation. Another challenge lies in the rendering of the pre-calculated data within the game engine itself. This requires the development of additional techniques for volume rendering, which is out of the scope of this paper.

The fire source was assumed to be located in room 351 as illustrated in **Fig.** ***6***, which is a room having a hospital bed on fire. **Fig.** *7* shows a screenshot of the fire and smoke from the player viewpoint.

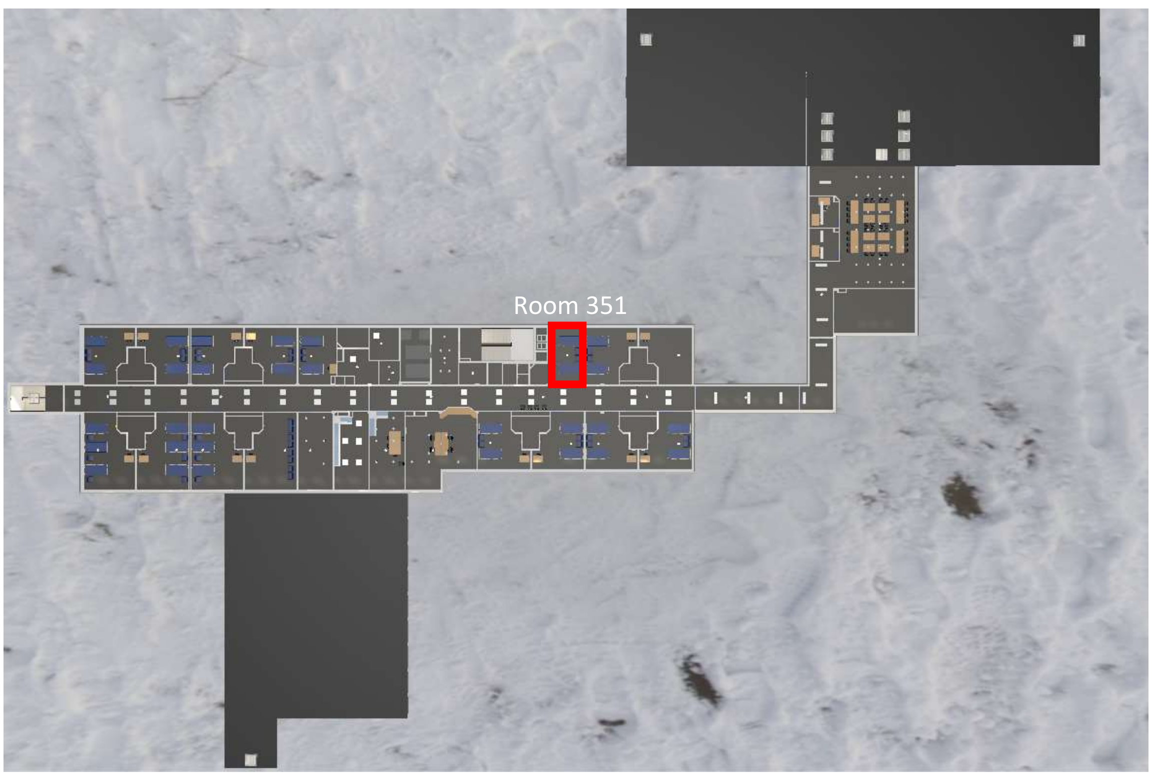


Fig. 6 The fire source location

Fig. 7 Screenshot taken during the gameplay to visualize the fire source

3.1.5 Storyline and learning objectives

The prototype proposes a single fire emergency scenario having the same learning objectives as the existing fire safety training adopted in the VVG hospital.

The content of the existing fire safety training consists of:

(1) the presentation of the goal of fire safety training;
(2) the basics about fire reaction;
(3) the concepts of announcement, alert, and alarm;
(4) the fire categories;
(5) the fire prevention measures such as compartmentation, fire detection, and alert message, the Belgian regulation and specific hospital regulation, extinction material (fire extinguishers, fire hoses, fire blankets, sprinklers), etc.;
(6) signage including emergency signs;
(7) evacuation procedure; and
(8) a fire detection scenario analysis is also discussed.

Thus, the game storyline was adapted to keep learning outcomes in line with the slide-based lecture expected learning outcomes. The game storyline and the associated learning objectives are described in the following paragraphs.

At the beginning of the simulation, participants are made aware of the role of the fire doors to guarantee compartmentation and evacuation routes through the first learning objective. The participants navigate in the virtual healthcare facility, where they face two chairs in front of a fire door (see **Fig. 8**-a). As the chairs inhibit the proper functioning of the route as well as the fire door, the objective consists of grabbing and storing these objects (i.e., the chairs) in an appropriate location.

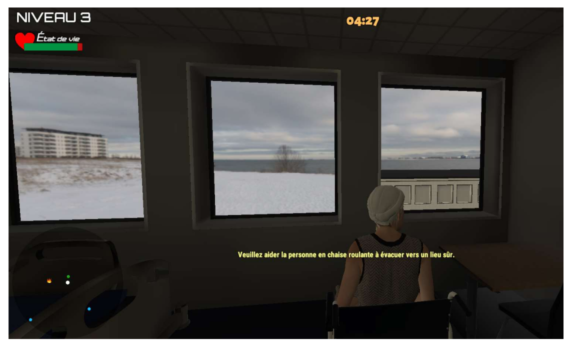
The second objective consists of using the alert button (i.e., the red button) to alert other staff members about the fire emergency (i.e., alarm internally) (see **Fig. 8**-b). The third objective consists of reaching the fire source location by following a colleague as it is recommended to check the situation accompanied by a colleague in case of a fire detection (see **Fig. 8**-c). This objective also requires the participant to check the temperature of the fire source premise's door before attempting to enter the premise. This is because, in the simulated scenario, the door is held closed, and the participant cannot assess what happens behind the door easily. Then, as the participant is instructed that the door temperature is hot once s/he assessed its temperature, the participant must ask her/his colleague to call the fire brigade (i.e., alarm externally) by using the correct phone number (i.e. (0)112). Then, s/he must ask her/his colleague to provide the correct information to the fire brigade (i.e., the address and the nature of the situation). Directly after the phone call, s/he is deemed to start to evacuate patients (i.e., assisted evacuation). It is recommended to start the evacuation with patients located in the critical triangle, which means that one needs to start with those in closest proximity to the fire room (i.e., right and left adjacent rooms). Thus, the fifth objective is to evacuate a patient from the right adjacent room to the fire room (see **Fig. 8**-d) and transport him/her to the nearest safe compartment using the wheelchair. Then, once the adjacent rooms are empty, it is recommended to evacuate the patients located in the rooms in front of the fire room (see **Fig. 8**-e). Therefore, the sixth objective is to evacuate these patients (i.e., a semi-ambulant patient and a bedridden patient). In this case, the participant can only evacuate a single patient at once. The second one would be evacuated by other caretaking staff members (i.e., modeled using NPCs). The objective here is to learn triage recommendations. As the objective of an evacuation is to evacuate as many people as it is possible in a short period of time, the participant should prioritize the patient with the highest walking capabilities (i.e., the semi-ambulant patient).

The seventh objective consists of carrying out the sweep of the compartment premises to make sure that no one is left behind. Finally, the eight's learning objective is to sensitize the participant about not returning to a premise, for example, to collect her/his personal items during evacuation. In this case, the participant had the possibility to return to a specific location to collect her/his cell phone (see **Fig. 8**-f) or to evacuate immediately. Once the participant reaches a place of safety (i.e., an adjacent compartment), the simulation ends, and a debriefing panel is displayed with the mistakes made during the simulation.

a- chairs blocking the fire door & evacuation route
Original text: “Ces chaises entravent votre chemin. Veuillez les ranger à leur place. Si jamais vous ne savez pas où les positionner, suivez les flèches noires.”
English translation: “These chairs block your path. Please grab and store them at a more appropriate location. If you don't know where to store them, follow the black arrows.”

b- alert button
Original text: “Appuyez sur le bouton poussoir avec le bouton gauche de la souris pour lancer l’alerte.”
English translation: “Press the red button using the left button of the mouse to trigger the alert.”

c- fire source location
Original text: “Suivez votre collègue.”
English translation: “Follow your colleague.”



d- patient, who required assistance from the player, located in an adjacent room
Original text: “Veuillez aider la personne en chaise roulante à évacuer vers un lieu sûr.”
English translation: “Please help the wheelchair user to reach a place of safety.”

e- bedridden and semi-ambulant patients, who required assistance from the player and other staff (NPCs), located in an adjacent room
Original text: “Il se trouve qu'il y a deux patients qui ont besoin de votre aide. Veuillez choisir lequel vous voulez aider.”
English translation: “Two patients are requiring your assistance. You need to select only one of them to provide your assistance.”

f- collectable cell phone and eyewear
Original text: “Votre téléphone portable est resté dans le bureau du personnel, vous pouvez aller le chercher et ensuite évacuer vers un lieu sûr ou bien vous pouvez évacuer immédiatement."
English translation: “You left your cell phone at the staff office. You can reach this office to collect it and then evacuate or to evacuate immediately.”

Fig. 8 Screenshots taken from the VR SG to illustrate the learning objectives of the simulated emergency scenario. The yellow text are instructions provided to the trainee during the gameplay in order to give hints to execute learning objectives easily. For easy reading, the original text which is in French was provided alongside its translation in English in the caption of each sub-figure.

3.2 Validation Procedure

This work provides a validation study of the proposed VR SG. This was done by comparing the SG training with the slide-based lecture used in the VVG hospital. The slides explain the basic fire safety recommendations and the theoretical fire safety concepts in line with the learning objectives listed in Section 3.1.5. This training method is considered as a passive learning method and was selected for this research to evaluate its effectiveness against the newly developed training alternative (based on the non-immersive VR SG).

To compare the effectiveness of the VR SG and the slideshow solutions, three tests were designed to collect participants' data, namely pre-test (i.e., before the training), post-test (i.e., immediately after the training), and retention-test (i.e., three to four weeks after the training), this approach is in line with the one used by Lovreglio *et al.* [22]. The full list of questions included in these tests, as well as the source of the scale used, are included in Appendix A. Fig. **9** presents the followed research methodology steps. To avoid biases in participants' self-reported responses due to gamification, researchers asked the VR group participants to take the experiment seriously or not participate if their objective was only entertainment.

The pre-test questionnaire included four sections:

1) The first one collected participants' demographics such as gender and age.

2) The second part assessed their background fire safety training experience and their evacuation drills experience. For the fire safety training experience, participants had the possibility to answer *"Never", "Once", "Twice", "More than twice" or "Uncertain"*. For the evacuation drills experience, participants had the possibility to answer "*Never", "Once a year", "Twice a year", "More than twice a year" or "Uncertain"*. Moreover, for the participants exposed to the non-immersive VR training they were asked to provide information about their gaming experience (i.e. how often they play video games on smartphones, consoles, or computers). Participants had the possibility to answer *"Never", "Less than once a year", "At least once a year", "At least once a month", "At least once a week", "Several days a week", or "Everyday"*.

3) The third part of the questionnaire measured participants' intrinsic motivation and self-efficacy levels. Intrinsic motivation was assessed with five questions adapted from the Interest/Enjoyment Scale from the Intrinsic Motivation Inventory [13], [28]. Self-efficacy regarding fire safety training was measured using five questions adapted from the Motivated Strategies for Learning Questionnaire (MSLQ) [13], [28]. The items in the intrinsic motivation questionnaire are: *"I enjoy fire safety training activities", "Fire safety training activities are fun to perform", "Fire safety training activities are boring", "Fire safety training activities do not hold my attention at all", and "I would describe fire safety training activities as very interesting"*. Respondents were asked to rate their level of agreement with the five items on a 7-point Likert scale (1= strongly disagree, 7= strongly agree). After the inversion of respondents' scores mentioned for the third and fourth answers in the intrinsic motivation questionnaire, for each respondent, the mean of his/her five answers was taken as the grouped Likert-scale score for intrinsic motivation. Similarly, the items in the self-efficacy questionnaire are*: "I am confident and can understand the basic concepts of fire safety", "I am confident that I understand the most complex concepts of fire safety", "I am confident that I can do an excellent job on the assignments and tests in fire safety exercises", "I expect to do well in fire safety training", and "I am certain that I can master the skills being taught during fire safety training sessions"*. Respondents were asked to rate their level of agreement with the five items on a 7-point Likert scale (1= strongly disagree, 7= strongly agree). For each respondent, the mean of his/her five answers was taken as the grouped Likert-scale score for self-efficacy.

4) The last part of the pre-test questionnaire assessed participants' knowledge of the basic fire safety recommendations. The knowledge test consisted of ten open-ended questions. This avoided prompting with possible answers or limited responses if close-ended questions are used. The knowledge answers were scored by the authors to provide a score ranging from 0 to 10 depending on the number of correct answers. An example of the scoring procedure is illustrated in Table 1. For instance, if we assume that participant 1 answered correctly the first, second and fifth questions and as each correct answer is worth one point, the total knowledge score for this participant is three.

Table 1 example on how knowledge answers were scored (N is the sample size)

	Participant ID					
Knowledge items	1	2	3	4	...	N
Move the objects to a proper location	1		1	1		1
Alert others	1	1	1	1		1
Call the internal emergency number "166" or trigger an alert button		1	1	1		1
Check if the door temperature is hot		1		1		1
Call the fire brigade	1	1		1		
Call the (0)112 by using a phone (or a DECT)		1		1		
Evacuate adjacent premises to the fire source first followed by the premises which are in front of the fire source		1		1		
Evacuate the patients to an adjacent compartment			1	1		
Evacuate the semi-ambulant patient first			1	1		
Leave personal items and evacuate immediately		1	1	1		1
Total Score	3	7	6	10	...	5

After completing the pre-test questionnaire, the slide-based training group received the slide-based lecture in a conference room on one of the campuses of the hospital center. This lecture was instructed by the prevention manager or by one of the prevention staff who was responsible for the fire safety training. During each session, the participants were instructed in groups of a maximum of 15 people. On the other hand, the VR-based training group played the game in a meeting room on one of the three campuses of the hospital center during working hours. A maximum of 2 participants participated at the same time per session. During the gameplay, two researchers were present providing procedural help when needed, meaning that only technically oriented help was provided when there were issues with the computer or gameplay.

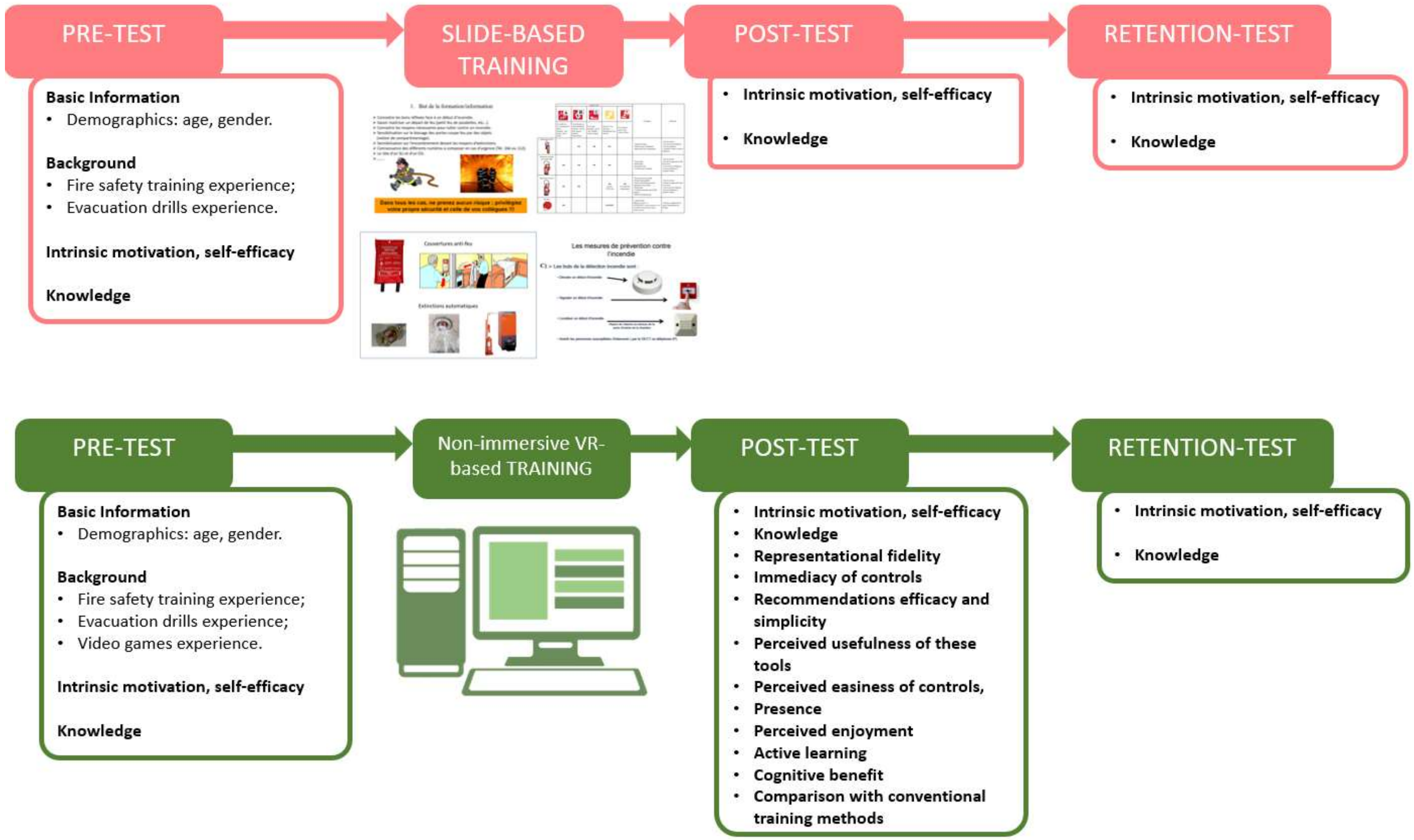


Fig. 9 Research methodology steps

Once the training was completed, the participants were asked to fill out a post-test questionnaire. This questionnaire included the same intrinsic motivation, self-efficacy, and knowledge tests as the pre-test. The VR-based training group participants were also asked to rate the non-immersive VR SG content using the following constructs: representational fidelity of the VW, the immediacy of controls, recommendations efficacy and simplicity, perceived usefulness of this tool, perceived ease of use, presence, perceived enjoyment, control and active learning, cognitive benefits, and to compare this training tool with slide-based training methods. Representational fidelity and immediacy of controls were assessed, each using three items adapted from [30]. Recommendations efficacy was assessed using two items from [22]; while recommendations simplicity was assessed using three items from [22]. Perceived usefulness was assessed using three items adapted from [31]. Perceived ease of use was assessed using three items adapted from [31]. The presence was assessed using four items adapted from [32]. Perceived enjoyment was assessed using three items adapted from [33]. Control and active learning constructs were assessed using four items adapted from [30]. The cognitive benefits construct was assessed using four items adapted from [30]. Finally, the comparison with slide-based training was carried out using three items adapted from [22]. All items with the exception of the knowledge test, used close-ended questions and a 7-point Likert scale (ranging from 1=strongly disagree to 7=strongly agree). After completion of the post-test questionnaire, participants were thanked for their participation.

Three to four weeks after the training, the same participants were asked to fill the retention test. This one included the same intrinsic motivation, self-efficacy, and knowledge questionnaires as the pre and post- tests.

3.2 Data analysis method

The data are visualized in this work using boxplots. Moreover, within- and between-group(s) analyses are conducted. The within-group analysis estimates the effectiveness of each individual intervention considering the following constructs: (a) knowledge acquisition; (b) knowledge retention; (c) intrinsic motivation improvement; and (d) self-efficacy level improvement. Given that the knowledge, intrinsic motivation and self-efficacy are measured using ordinal scales and that the collected data are not normally distributed, Mann-Whitney u-test was used to assess whether there are statistically significant differences within the experimental groups' self-reported answers and at different points of assessment. The level of significance used is fixed to 0.05. The between-groups analyses compare both interventions considering the same above-mentioned variables and using Mann-Whitney u-test for the same reasons. Finally, data analysis assesses the non-immersive VR SG content considering the following additional measurements: (e) the representational fidelity; (f) the immediacy of controls; (g) the efficacy and simplicity of the recommendations; (h) the perceived usefulness of these tools; (i) the perceived ease of use; (j) the presence; (k) the perceived enjoyment; (l) the control and active learning; (m) the cognitive benefits; and (n) the comparison with slide-based training methods.

4 Validation Results

4.1 Participants

Hereafter, it is referred to the used slideshow for training as the conventional slide-based training (CT). The sample consisted of 78 staff members of VVG hospital (47 from the CT group and 31 from the VR-based training group). 52 of them were females (44 from the CT group and 8 from the VR-based training group) and 26 were males (3 from the CT group and 23 from the VR-based training group). They were volunteers and did not receive compensation for participating in this study. Participants' age ranged from 24 to 62 years old (Mean = 45.4, SD = 8.6) for the CT group; while it ranged from 25 to 64 years old (Mean = 40.4, SD = 12.0) for the VR-based training group.

The VR-based training group seems to have more males in the group than females, whereas the CT group seems to have more females in the group than males. As explained below, due to organizational procedures, it was not possible to have a balanced sample containing an equivalent number of males and females in either group. Therefore, in this study, we will investigate if the gender variable influences the knowledge, intrinsic motivation, and self-efficacy gains (see Section 4.5). Moreover, the CT group seems to have older participants than the VR-based training group. There is a statistically significant age difference when comparing both groups (Mann-Whitney u-test, p-value = 0.039, Z = -2.064, and r = $Z/\sqrt{N}$ = - 0.234, which is the effect size). Therefore, in this study, we will also investigate if the age variable influences the knowledge, intrinsic motivation and self-efficacy gains (see Section 4.5). Participants' fire safety previous experience (FSPE), their evacuation drills previous experience (EDPE), and their gaming experience are illustrated in Figs. 10 and 11.

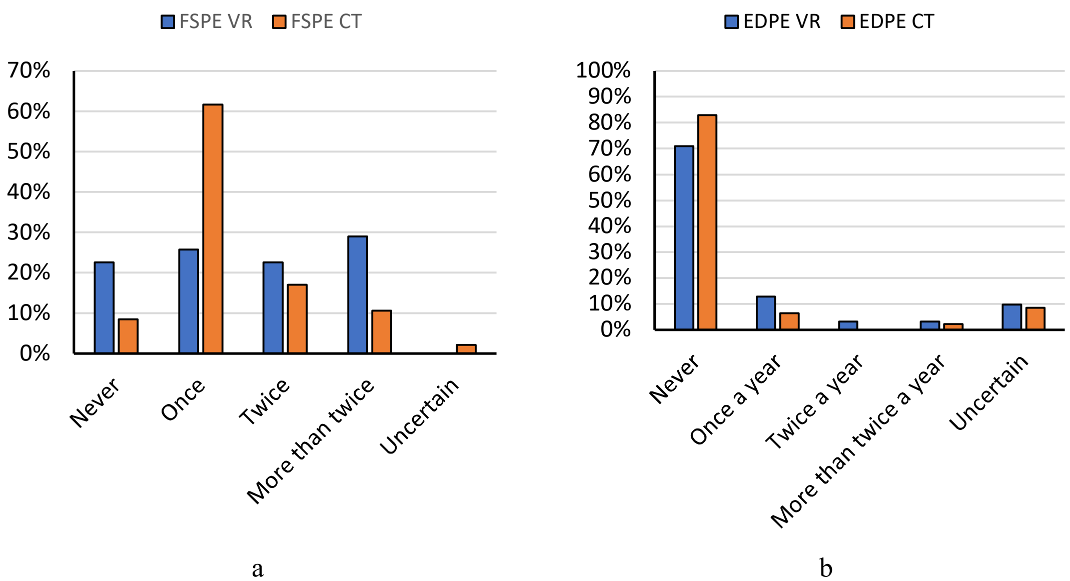


Fig. 10 Participants' previous fire safety training experience (FSPE) (a) and their evacuation drills previous experience (EDPE) (b) for the VR-based training group, and the slide-based training group

From **Fig. 10**-a, we can observe that most participants had participated in fire safety training at least once. From **Fig. 10**-b, we can notice that most participants reported never participating in fire drills. Two chi-squared tests were carried out to investigate the statistical difference between the CT and VR-based training groups. The results indicate that there is no significant difference between the two groups in terms of participants who received previous fire safety training.

From **Fig. 11**, we can note that approximately half of the participants of the VR-based training session never plays video games. In addition, approximately 75% of participants reported playing video games less than once a month. From these results, we can conclude that most participants of the VR-based training group are not used to play video games.

It was not possible to randomize participants' assignment to a specific experimental group due to practical limitations, as the staff needed to subscribe for the fire safety training on a voluntary basis (i.e., the hospital disposes of a large pool of staff such as administrative staff, nurses, cleaning personnel, doctors, technical staff, etc. who work in shifts). Therefore, randomization was implemented on the group level (i.e., a group was composed of people who subscribed for fire safety training on the same date). Participants' role in the hospital was no assessed directly but the researchers who participated in the organization of the training sessions confirmed, from discussions with the safety educators and participants, that: (1) the slideshow participants came from the same department (cleaning department) as it was necessary to recycle the training of these individuals; and, (2) the VR-based group participants came from different departments due to organizational constraints.

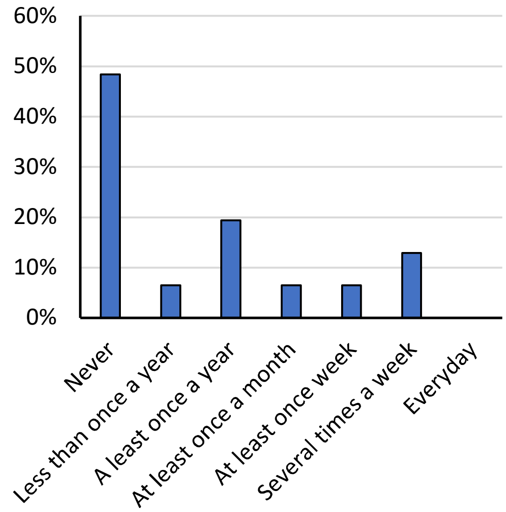


Fig. 11 VR-based training group participants' video games experience

4.2 Knowledge assessment

In this section, knowledge scores obtained by the participants are analyzed by splitting them depending on the training group (i.e., VR-based training and slideshow training) and when the assessment occurred (i.e., before the training, after the training and after three to four weeks). **Fig. 12** shows knowledge scores data. Regardless of the difference between the training groups in terms of initial knowledge (i.e., the group exposed to the VR-based training had a slightly higher initial knowledge than the group exposed to the slide-based training), we can notice that:

1) for the VR-based training group, there is a significant increment of knowledge immediately after the training. Indeed, the mean pre-training score was 4.55 ± 2.39 (sample size $N = 31$, and Cronbach's alpha = 0.72); while the mean post-training score was 7.23 ± 2.74 (sample size $N = 31$, and Cronbach's alpha = 0.83). In addition, the acquired knowledge seems to be maintained three to four weeks after the training as the mean retention score was 7.80 ± 1.75 (sample size $N = 10$, and Cronbach's alpha = 0.61).
2) for the CT group, there is also a significant increment of knowledge immediately after the training session. However, this increment is less marked than the group exposed to the VR SG. Indeed, the mean pre-training score was 4.28 ± 1.99 (sample size $N = 47$, and Cronbach's alpha =0.58); while the mean post-training score was 5.23 ± 2.88 (sample size $N = 47$, and Cronbach's alpha =0.82). In addition, participants knowledge dropped slightly three to four weeks after the experiment as the mean retention score was 5.17 ± 2.06 (sample size $N = 43$, and Cronbach's alpha = 0.60).

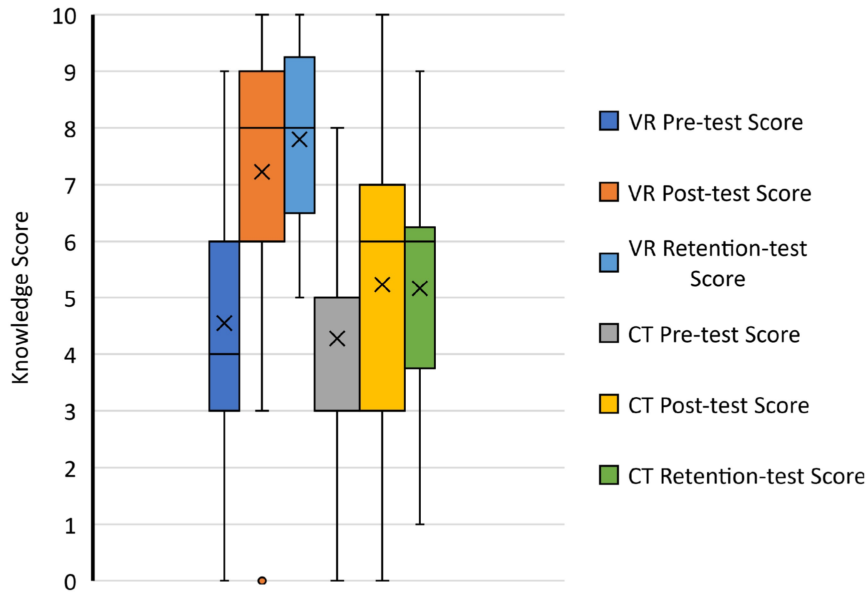


Fig. 12 Participants mean scores distribution before the training (Pre), after the training (Post) and after three to four weeks (Ret) for the VR-based training and the CT groups

Mann-Whitney u-test results when comparing knowledge scores obtained in the pre-, post- and retention tests for either intervention are reported in Table 2.

Table 2 Within-group comparisons regarding the knowledge scores according to the point of assessment

	Slideshow		VR application	
	p-value	**Effect Size**	**p-value**	**Effect Size**
Pre-test x Post-test	0.020	- 0.241	0.000	- 0.496
Pre-test x Ret-test	0.026	- 0.235	0.000	- 0.555
Post -test x Ret-test	0.669	- 0.045	0.545	- 0.102

From Table 2, it can be noticed that the knowledge of participants before and immediately after the training was statistically different for both groups as a significant increment of knowledge was observed for both groups directly after the training. A similar trend was observed when comparing the knowledge scores before and three to four weeks after the training. Finally, no statistically significant difference was observed when comparing the performance in the post-test and retention test for both experimental groups.

In addition to the above-mentioned analysis, a between-group analysis is carried out in order to highlight if there was any statistically significant difference between the groups regarding knowledge scores in the three points of assessment (see Table 3).

Table 3 Between-groups comparison regarding knowledge scores in the three points of assessment

	Pre-test		Post-test		Retention-test	
	p-value	Effect size	p-value	Effect size	p-value	Effect size
Slideshow x VR application	0.864	- 0.019	0.001	- 0.367	0.001	- 0.214

Table 3 results show that there was no statistically significant difference when comparing the initial knowledge of participants (p-value is well above the level of significance of 0.05). On the other hand, there was a statistically significant difference when comparing post-tests results between slide-based training group and VR-based training group. This is because the mean knowledge gain value observed for participants of the VR-based training group (i.e., of 2.68) was more than twice the mean knowledge gain value observed for participants of the slide-based training group (i.e. of 0.95). A similar trend was observed when comparing retention test results. Indeed, there was a statistically significant difference when comparing the knowledge scores of participants three to four weeks after the experiment was completed.

4.3 Intrinsic motivation assessment

In this section, participants' intrinsic motivation answers are analyzed by splitting them depending on the group (i.e., VR-based training and CT) and when the assessment occurred (i.e., before the training, after the training, and after three to four weeks). **Fig. 13** shows the intrinsic motivation scores for each group and when the assessment occurred. For the VR-based training group, the mean pre-training score was 5.54 ± 1.13 (sample size $N = 31$, and Cronbach's alpha = 0.84); while the mean post-training score was 6.00 ± 0.86 (sample size $N = 31$, and Cronbach's alpha = 0.74); and the mean retention score was 5.98 ± 0.70 (sample size $N = 10$, and Cronbach's alpha = 0.81). For the CT group, the mean pre-training score was 5.25 ± 1.12 (sample size $N = 47$, and Cronbach's alpha = 0.66); while the mean post-training score was 5.03 ± 0.99 (sample size $N = 47$, and Cronbach's alpha = 0.64); and the mean retention score was 5.39 ± 1.07 (sample size $N = 43$, and Cronbach's alpha = 0.70).

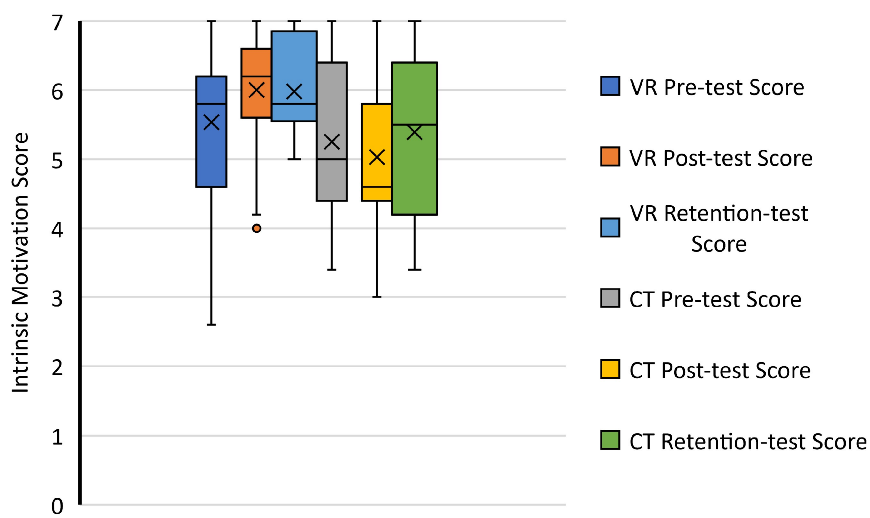


Fig. 13 Intrinsic motivation mean scores before the training (Pre), after the training (Post) and after three to four weeks for the VR-based training and the CT groups

For the VR-based training group, results in **Fig. 13** show a slight increment of intrinsic motivation immediately after the training, and this motivation seems to be maintained three to four weeks after the training even if a slight drop of motivation after this period of time was observed. Conversely, for the slide-based training group, results in **Fig. 13** show a decrease of intrinsic motivation immediately after the training and an increment of motivation three to four weeks after the training. Even if we observe an increment of motivation after three to four weeks after the experiment for the group who received the training through a lecture, this increment is still below the motivation levels reported by participants of the VR-based training group.

Mann-Whitney u-test results when comparing intrinsic motivation scores obtained in the pre-, post- and retention tests for either intervention are reported in Table 4.

Table 4 Within-group comparisons regarding the intrinsic motivation scores according to the point of assessment

	Slideshow		**VR application**	
	p-value	**Effect size**	**p-value**	**Effect size**
Pre-test x Post-test	0.313	- 0.104	0.094	- 0.213
Pre-test x Ret-test	0.575	- 0.059	0.874	- 0.029
Post -test x Ret-test	0.147	- 0.154	0.354	- 0.152

Results in Table 4 reveal that there was no statistically significant difference between motivation scores before, immediately after the training and three to four weeks after the training for both groups.

Moreover, a between-group analysis was performed to show if there was any difference between the groups in terms of initial motivation, the motivation measured immediately after the training, and the one measured three to four weeks after the training. The results are presented in Table 5.

Table 5 Between-groups comparison regarding intrinsic motivation scores in the three points of assessment

	Pre-test		**Post-test**		**Retention-test**	
	p-value	Effect size	p-value	Effect size	p-value	Effect size
Slideshow x VR application	0.252	- 0.130	0.000	- 0.450	0.173	- 0.189

Table 5 results reveal no statistically significant difference between the groups' initial conditions. However, there was a statistically significant difference between the groups' intrinsic motivation when comparing the scores immediately after the training. Indeed, participants in the VR training group showed a higher motivation immediately after the training than participants in the CT group. Finally, after three to four weeks after the training, both groups showed the same level of motivation. Indeed, there was no statistically significant difference between the groups when comparing retention-test intrinsic motivation levels.

4.4 Self-efficacy assessment

In this section, participants' self-efficacy answers are analyzed by splitting them depending on the group (i.e., VR-based training and CT) and when the assessment occurred (i.e., before the training, after the training and after three to four weeks). **Fig. 14** shows the self-efficacy scores for each group and when the assessment occurred. For the VR-based training group, the mean pre-training score was 4.99 ± 1.01 (sample size $N = 31$, and Cronbach's alpha = 0.90); while the mean post-training score was 5.61 ± 0.86 (sample size $N = 31$, and Cronbach's alpha = 0.94); and the mean retention test score was 5.82 ± 0.54 (sample size $N = 10$, and Cronbach's alpha = 0.89). For the CT group, the mean pre-training score was 4.99 ± 1.26 (sample size $N = 47$, and Cronbach's alpha = 0.90); while the mean post-training score was 5.22 ± 1.06 (sample size $N = 47$, and Cronbach's alpha = 0.90); and the mean retention score was 4.82 ± 1.04 (sample size $N = 43$, and Cronbach's alpha = 0.90).

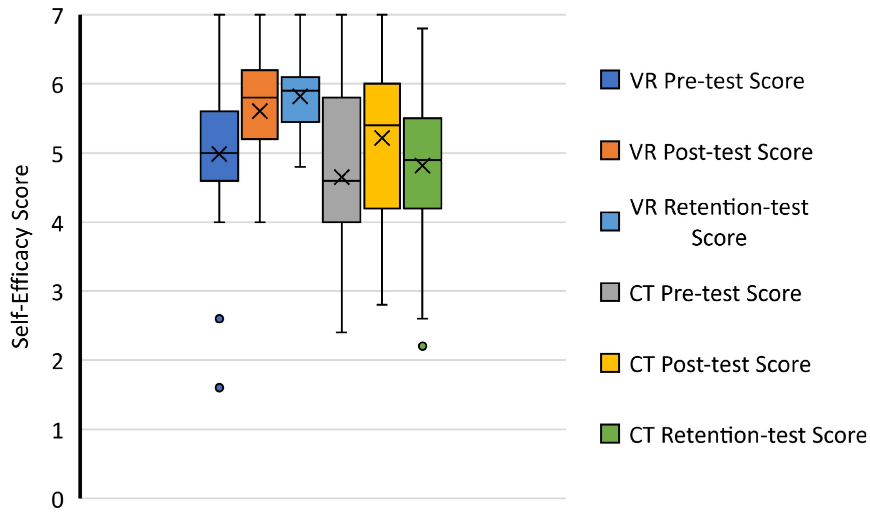


Fig. 14 Self-efficacy mean scores before the training (Pre), after the training (Post) and after three to four weeks for the VR training and CT groups

Fig. 14 results show that there was an increment of self-efficacy immediately after the training for both groups. It can also be noticed that this level of self-efficacy seems to be maintained (not to say, it is higher than the self-efficacy levels measured prior and immediately after the training) three to four weeks after the training for the group members who were exposed to the VR-based training. Conversely, for the group members who received training through a lecture, a drop in self-efficacy level can be observed after three to four weeks after the experiment. Another observation is that participants of the CT group gained more confidence than participants of the VR-based training immediately after the training. This can be due to the fact that the initial self-efficacy level of the VR-based training group was already high compared with the initial self-efficacy level of the CT group.

Mann-Whitney u-test results when comparing self-efficacy scores obtained in the pre-, post-, and retention tests for either intervention are reported in Table 6.

Table 6 Within-group comparisons regarding the self-efficacy scores according to the point of assessment

	Slideshow		**VR application**	
	p-value	**Effect size**	**p-value**	**Effect size**
Pre-test x Post-test	0.031	- 0.222	0.010	- 0.328
Pre-test x Ret-test	0.374	- 0.094	0.020	- 0.366
Post -test x Ret-test	0.091	- 0.179	1.000	0.000

Table 6 results show that the self-efficacy level reported by participants before and immediately after the training was statistically different for both groups as a significant increment of self-efficacy was observed for both groups immediately after the training. A similar trend was observed when comparing the self-efficacy levels before and three to four weeks after the training for the group exposed to the VR SG; while no statistically significant difference was observed when comparing the self-efficacy level before the experiment and after three to four weeks after the experiment for the CT group. This observation is probably due to the fact that, for the CT group, there was a significant drop in the acquired self-efficacy after three to four weeks after the experiment. Finally, no statistically significant difference was observed when comparing participants' self-efficacy level in the post- and retention tests for both groups.

In addition, a between-group analysis is conducted to investigate if there was any statistical difference between the groups' initial conditions in terms of self-efficacy level, but also between groups conditions immediately after the experiments and three to four weeks after the experiments. Table 7 reports the associated results.

Table 7 Between-groups comparison regarding self-efficacy scores in the three points of assessment

	Pre-test		**Post-test**		**Retention-test**	
	p-value	Effect size	p-value	Effect size	p-value	Effect size
Slideshow x VR application	0.131	- 0.058	0.112	- 0.180	0.004	- 0.399

According to Table 7 results, the initial conditions between the groups are similar as there was no statistical difference between the groups before the experiments. The same trend was observed for post-training results as there was no statistical difference between post-training results. Conversely, there was a statistically significant difference when comparing the self-efficacy scores reported by participants three to four weeks after the training.

4.5 Gender and age influence on participants' knowledge, motivation and self-efficacy gains

Knowledge, intrinsic motivation, and self-efficacy gains are calculated using the difference between pre and post-experiment data. On the one hand, to verify whether the age difference had an influence on these gains, we checked if there were correlations between these gains and participants' age. This was carried out using a linear regression showing that the influence of age on knowledge, intrinsic motivation and self-efficacy gains, was not statistically significant (Knowledge gain p-value = 0.439; intrinsic motivation p-value = 0.290; self-efficacy p-value = 0.222. One can observe that all p-values are above the level of significance of 0.05). On the other hand, the statistical analysis used for the age variable cannot be used to verify the impact of gender on the above-outlined variables as CT group has only 3 male participants. Therefore, the impact of gender on the different variables was only assessed for the VR group and confirmed that there was no significant impact of gender on the assessed metrics (Knowledge gain p-value = 0.142; intrinsic motivation p-value = 0.108; self-efficacy p-value = 0.583. One can observe that all p-values are above the level of significance of 0.05).

4.6 VR application assessment

Fig. 15 shows participants' boxplots ratings of the constructs considered for the VR application content assessment. These constructs are the following: (1) representational fidelity, mean = 5.40 ± 1.49 (Cronbach's alpha = 0.94), (2) immediacy of controls, mean = 5.31 ± 1.37 (Cronbach's alpha = 0.94), (3) recommendations efficacy, mean = 5.89 ± 0.93 (Cronbach's alpha = 0.72), (4) recommendations simplicity, mean = 5.90 ± 0.95 (Cronbach's alpha = 0.91), (5) perceived usefulness, mean = 5.20 ± 1.43 (Cronbach's alpha = 0.93), (6) perceived ease of use, mean = 4.66 ± 1.63 (Cronbach's alpha = 0.82), (7) presence, mean = 4.31 ± 1.26 (Cronbach's alpha = 0.79), (8) perceived enjoyment, mean= 5.48 ± 1.38 (Cronbach's alpha = 0.87), (9) control and active learning, mean= 5.25 ± 1.10 (Cronbach's alpha = 0.95), (10) cognitive benefits, mean= 5.57 ± 1.11 (Cronbach's alpha = 0.92), and (11) comparison with slide-based training, mean= 5.12 ± 1.31 (Cronbach's alpha = 0.83).

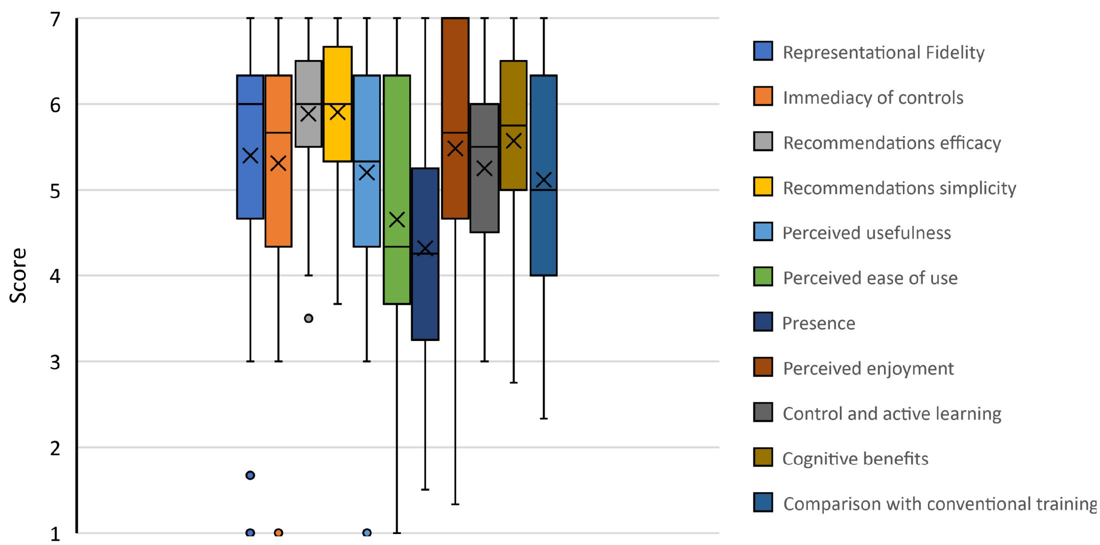


Fig. 15 Participants boxplots ratings of the VR-based simulation assessment constructs

5 Discussion and limitations

This study describes the prototyping steps required to develop a non-immersive VR SG to train the staff of VVG hospital.

The creation of the geometry of actual buildings in a game engine itself represents one of the main challenges when developing a VR-based SG. Several technologies, such as the use of point clouds, are still too expensive and impractical. As such, in this study, we used an efficient and cost-effective alternative to develop a replica of actual buildings using a BIM solution. Section 3.1 shows the steps required to use BIM tools to develop a realistic replica of a building using Autodesk Revit and Unity3D. The workflow highlights that while the building geometry was developed using BIM, the realism of the virtual environment can be enhanced by furniture and lightmapping (i.e., simulation of the light casting in the environment). However, this alternative solution still requires a compromise between the computational resources available (especially the graphic card performance) and the level of detail and realism of the virtual scene. This compromise needs to be found in order to allow an adequate frame rate per second during the full virtual experience.

Interactions between the player and the virtual objects are also key components that were considered in in the development of the proposed VR SG. New and existing Unity scripts were employed in the development to allow the player to interact with the objects and NPCs in the virtual environment. NPCs are another key component of the simulator as they allow to populate the virtual world with other characters than the user and to facilitate social interactions during fire emergencies. Indeed, in a healthcare facility building, people are not alone. Various profiles of occupants are present in such environments such as patients, visitors, and staff. Therefore, the simulated hospital was populated with various NPCs having different profiles, attributes, and behaviors. Some of those interacted with the user during the gameplay, while others were not interactive. The reason why all NPCs were not interactive is that it was a trade-off between the accuracy of NPCs behaviors and the development and computational resources available.

Representation of the fire and smoke modeling is another key challenge of the SG development. Fire and smoke were represented in this work using particle systems, which provide a qualitative representation of the threat. This represents a feasible solution to develop SGs as highlighted in previous literature [40]. Section 3.1.4 provides a description of the quantitative alternative which future SG developers could use. However, this second more advanced option requires third-party CFD software tools to pre-simulate fire and smoke spread and challenging data conventions to import the data into the game engine. Readers can refer to these references for a discussion on this second approach [41] and [42].

Finally, it is also fundamental to define the learning outcomes of the training and introduce them through a well-designed storyline. The storyline shown in Section 3.1.5 included all the learning objectives of the existing fire safety training adopted in the VVG hospital. As such, it is fundamental while developing the game storyline to have events in the game which give the user the possibility to learn each single learning outcome. The SG solution proposed in this work has the advantage of providing a customized feedback report at the end of the training, which shows users the mistakes they made and what are more appropriate behaviors. This customized feedback is instead very difficult to achieve in traditional training like evacuation drills as explained by Gwynne *et al.* in [4].

This work also provides a validation study of the proposed VR-based SG. We evaluated the effectiveness of this tool against a slide-based lecture used by VVG hospital safety educators for fire safety training in terms of participants' knowledge acquisition and retention as well as their changes in attitudes such as intrinsic motivation and self-efficacy.

Knowledge results showed that both groups of participants had the same initial knowledge and that they knew only half of the answers before the training. Both training methods significantly increased participants' knowledge about fire safety recommendations immediately after the training. However, the greatest increment of knowledge was observed for participants of the VR-based training group. This can be explained by several reasons. First, the VR-based training may have seduced the participants by gameplay, which may increase their attention to the training content. Second, the interactivity of the VR SG may also increase participants' attention and thus results in deeper processing and memorization of the training content. Third, the fact that participants were engaged in the performance of the activity themselves may also enhance their engagement in the performance of the tasks presented in the VR SG, which may lead to better learning. Similar observations were made in analyses which compared CT methods with VR-based training methods, such as [3], [12], [15], [18], [22], [25], and [34]. From these studies, the only one that compared a slide-based lecture with VR-based fire safety training in a healthcare context was carried out by All *et al*. [3]. The observations regarding knowledge enhancement made in the present study are consistent with those made in [3]. The long-term effects of training on trainees' knowledge was not assessed by All *et al.* [3] even if they considered this as an added value. This was thus addressed in the present study. The results regarding knowledge retention highlighted that participants who learned through the VR-based training maintained the acquired knowledge even three to four weeks after the training, while participants who learned through the slide-based lecture had shown a slight drop of knowledge three to four weeks after the training. This observation is consistent with previous observations made in [22].

The intrinsic motivation results did not reveal any significant improvement with either intervention. However, it must be noted that, in the present study, for the VR-based training group, the pre-training mean score was already high (5.54 on a 1 to 7 scale). Thus, the lack of significance may be related to a ceiling effect. For the slide-based training, participants motivation scores decreased immediately after the training. This might be explained by a lack of interest of participants in fire safety training displayed through this medium. Moreover, it can be noted that the levels of motivation reported by participants are higher for the group who received training through the VR application than the remaining group. These observations are in accordance with our expectations and with observations made in [3]. Indeed, a VR-based approach could make the training more interactive, appealing, and rewarding compared to the slide-based approach, where trainees learn in a passive way and may feel bored.

Our analysis revealed a statistically significant increase in self-efficacy levels immediately after the training in both experimental groups. Indeed, participants of either group reported higher self-efficacy levels about their ability to deal with fire emergencies after the training compared to the levels reported before the training. Therefore, both training methods could successfully improve this aspect of participants' attitudes. Moreover, no statistically significant differences were observed between the groups in terms of self-efficacy before and immediately after the training; however, a statistically significant difference was observed between the experimental groups when comparing the self-efficacy results after three to four weeks after the training. Indeed, the VR-based training group maintained the same level of self-efficacy as the post-training, while the CT group showed a slight decrease in self-efficacy level after three to four weeks after the training. Therefore, both training methods have a comparable effect in improving short term self-efficacy, whereas VR-based training can be considered as more effective than the slide-based lecture in improving long-term self-efficacy. These results support the adoption of VR-based education methods in a healthcare context to increase self-efficacy towards fire safety training.

The results regarding the VR SG content assessment indicated that the great majority of the participants who tried this medium had a positive perception of it. This observation is in accordance with previous studies such as [22]. Participants reported that the virtual environment was represented as close to the real building. They also rated the simulator controls positively with a mean score of 5.31 on a 1 to 7 scale. They agreed that the simulator provided simple and effective recommendations and perceived that training through this medium as useful for improving knowledge. However, using the mouse and keyboard for navigation in the VW and for interaction with the virtual objects was not easy to deal with for all participants of the VR training group. In this case, the mean score was 4.66, which is slightly above the neutral score of 4. This is because most participants were not familiar with video games. In addition, people did not feel absorbed in the virtual experience. Indeed, the presence mean score was 4.31. This could be due to the fact that the game was displayed on the computer screen. Probably, using Immersive VR could improve the sense of the presence of participants. They also enjoyed the VR experience and agreed that the VR-based training solution promoted active learning at their self-pace, as well as a better overview and better control of the acquired knowledge. In addition, participants agreed that learning through VR makes the understanding of fire safety rules easier, simple to remember, and to apply to real-life scenarios. This was reflected by a mean score of 5.57 for the cognitive benefits construct. Finally, participants recommended the VR-based training method over the slide-based training method even if the mean score reported (of 5.12) was not well above the neutral score. This highlighted that training through this medium has great potential in a healthcare context, even if this technology cannot replace hands-on training where people can feel the heat on their faces, smell the smoke, and can use an actual fire extinguisher to put out a fire. This training solution could, however, be a great complement to existing training methods.

Data collection in healthcare facilities is challenging; therefore, the present study has a set of limitations greatly influenced by the fact that randomization was not possible given the constraints of the collaborating hospital. A first limitation of the comparative study lies in the nature of the sample, obtained through convenience sampling. This limitation could be explained as follows: the experiment schedule was highly influenced by the fact that participation was on a voluntary basis but also because of the hospital's training schedule. That is why, the experimenters were not able to guarantee evenly distributed samples with an equal number of males and females even if the initial objective was to get an ideal sample. The difference in gender between the experimental groups is not a major issue as existing studies, such as [35, 36, and 37], have shown that this variable does not have any impact on safety training. For instance, Gélinas-Phaneuf *et al.* [35] have shown that there was no statistically significant influence of gender on the different performance metrics assessed using an experiment with a neurosurgical VR tool; Grantcharov *et al.* [36] showed that there was no statistically significant difference between genders error scores using VR clinical training experiment for laparoscopy; and, Kinateder *et al.* [37] observed no difference in terms of fire safety behaviors in the group who was trained using a VR simulator.

For the slide-based training group, training focused on participants from the same department (cleaning department) as it was necessary to recycle the training of these individuals, as explained in Section 4.1. Whereas, for the VR-based training group, participants were from different departments. However, participants' role in the hospital was not monitored explicitly. This could be an interesting thread for future developments. Indeed, the role in the hospital and probably the degree of education might influence the results, and this impact should be investigated in further detail. Seniority is another variable that can influence the results. However, the present research does not investigate the influence of seniority on the outcome of training. This could be a second research question that can be investigated in the future. In addition, participants of the slide-based training group seem to be older than participants of the VR-based training group. However, the pre-training knowledge of fire safety rules, as well as the pre-test motivation and self-efficacy of both groups, are similar. This is also in line with the fact that the two groups received a similar amount of fire safety training.

As shown in Section 4.5, the age difference did not influence participants' knowledge, intrinsic motivation, and self-efficacy gains. Future research must also focus on the comparison between VR SG(s) with the practice of fire safety recommendations/procedures instead of using only slideshows. Another limitation of this study is that participants of the VR-based training group did not all respond to the retention test (only 10 participants from 31 answered the retention test). This may influence the credibility and validity of the long-term results. There was no distinction made between general fire safety and healthcare fire safety (i.e., in a clinical setting); however, this could probably influence the results and might be interesting to consider in future research.

Further limitations are related to non-immersive VR itself. For instance, the usage of standard game controls and displays such as a flat-screens, a keyboard, and a mouse is likely to influence the results. Moreover, some participants (mainly those not familiar with games) were not familiar with this type of control, which is reflected by the low rating of the "ease of use" construct. This issue also influenced their degree of immersion and sense of "Presence". This limitation could be overcome by using fully immersive VR equipment that uses headsets and associated VR handset controllers such as the HTC VR equipment or the Oculus one. This is a research question that would be explored in the future. Indeed, we are working on a fully immersive version of the same scenario, which requires a thorough adaptation of the game to consider the various techniques employed in immersive VR. The enjoyment construct was only assessed for the VR-based training group; however, this variable could be worth investigating in the future in order to compare the difference in the enjoyment of the training regardless of its nature.

A final aspect, which was not investigated in this research, is how much trainees took both VR-based and slide-based training seriously. Giving the gaming nature of the VR-based training, there is the possibility that trainees will not take seriously the instruction learned through a videogame. As such, further research is necessary to investigate the impact of gamification features in the fire safety training domain.

6 Conclusion

The use of VR for fire safety training in a healthcare context has been rarely studied. This research paper advances knowledge about the topic by proposing a novel non-immersive VR SG to train hospital staff. The work describes the challenges to address while developing the key components of the game, such as the digital replica of an existing hospital, players' navigation and interaction, non-playable characters, fire and smoke spread, and the storyline.

The proposed prototype was validated by comparing it with conventional slide-based training in terms of increment of knowledge of fire safety rules, as well as intrinsic motivation and self-efficacy regarding fire safety training. Overall, the results revealed that the non-immersive VR-based training could be more effective than slide-based training to enhance participants' knowledge about fire safety rules as well as the retention of the acquired knowledge. The use of this solution for training also has a positive effect on participants' attitudes, such as self-efficacy. Conversely, either training approach has not increased much participants' intrinsic motivation, which was already high prior to the training. Finally, even if participants well-rated most aspects of the VR application content, the ease of use and sense of presence (or immersion) could be improved in the future.

Ethical considerations

The ethics committee of the University of Mons has reviewed and approved this research. Participants were informed about the purpose of the study via an information sheet and signed a consent form for data collection and storage before undertaking the training. They were also informed that they had the possibility to stop the experiment at any time without any reason and that they can stop the experiment if they feel sick or any discomfort. All the training sessions were performed under the supervision of at least one researcher in case of an emergency.

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Appendix A *Questionnaires items and their source*

Construct	***Items***	***Source***
Intrinsic Motivation	1. I enjoy fire safety training activities. 2. Fire safety training activities are fun to perform. 3. Fire safety training activities are boring. 4. Fire safety training activities do not hold my attention at all. 5. I would describe fire safety training activities as very interesting.	Deci *et al*. (1994); Makransky & Peterson (2019)
Self-efficacy	1. I am confident and I can understand the basic concepts of fire safety. 2. I am confident that I understand the most complex concepts of fire safety. 3. I am confident that I can do an excellent job on the assignments and tests in fire safety exercises. 4. I expect to do well in fire safety training. 5. I am certain that I can master the skills being taught during fire safety training sessions.	Deci *et al*. (1994); Makransky & Peterson (2019)
Knowledge	1. If you are inside a building of the hospital centre and you noticed an object inhibiting the functioning of a fire door (or an emergency exit) in case of fire, what would you do? 2. If you are facing a small fire which was not detected via automatic smoke detectors (i.e. no internal or external alarm), what would you do first? 3. How would you perform this action? 4. If a fire is announced (i.e. internal alarm only) and you are in front of a confined room where the fire was detected, what would you do first? 5. If you are facing a gaze, what would you do first? 6. How would you perform this action? 7. If the evacuation of patients is required, where would you transport patients? 8. During evacuation, if several rooms are occupied by patients, in which order would you evacuate them? 9. During evacuation, if you are in a room where two patients with different degrees of mobility (i.e. a semi-ambulant patient and an immobile (or bedridden patient) patient) require your help, which one would you assist first? 10. During evacuation, if you notice that you forgot a personal item such as you cell phone, what would you do?	-
Representational fidelity	1. The realism of the virtual world motivates me to learn. 2. The virtual world makes learning more interesting. 3. The realism of the virtual world enhances my learning.	Lee *et al*. (2010)
Immediacy of controls	1. The ability to manipulate the 3D objects in the virtual world allows me to learn better. 2. The ability to manipulate the 3D objects in the virtual world makes learning more motivating and more interesting. 3. The ability to manipulate the 3D objects in the virtual world in real-time helps me to learn better.	Lee *et al*. (2010)
Recommendations efficacy	1. The recommendations provided in the training experience are useful for my safety. 2. Recommendations provided in the training experience are will help me to effectively act in real-life fire situations.	Lovreglio *et al*. (2020)

Recommendations simplicity	1. I could easily learn the recommendations provided in the virtual experience. 2. I could easily remember the recommendations provided in the virtual experience. 3. I could easily carry out the recommendations provided in the virtual experience.	Lovreglio *et al*. (2020)
Perceived usefulness	1. Using this type of virtual reality simulation as an educational tool will enhance my learning. 2. This type of simulation will allow me to progress at my own pace. 3. This type of simulation is useful as a learning supplement.	Davis (1989)
Perceived ease of use	1. Manipulating this simulation tool is ease for me. 2. Manipulating this simulation tool is too complicated for me. 3. Overall, I think this training tool easy to use.	Davis (1989)
Presence	1. My interactions with the virtual objects seemed to be natural. 2. My experience in the virtual world seemed consistent with real-life experiences. 3. I was engaged in the virtual world experience. 4. I was involved in the experimental task to the extent that I lost track of time.	Sutcliffe *et al*. (2005)
Perceived enjoyment	1. I find using this fire simulator enjoyable. 2. Using this fire simulator is pleasant. 3. I have fun using this fire simulator.	Tokel & Isler (2015)
Control & active learning	1. This learning method helps me to have a better overview of the content learned. 2. This learning method allows me to be more active in the learning process. 3. This learning method allows me to have more control over my own learning. 4. This learning method allows promotes self-paced learning.	Lee *et al*. (2010)
Cognitive benefits	1. This simulator makes the comprehension easier. 2. This simulator makes the memorisation easier. 3. This simulator helps me to better apply what was learned. 4. This simulator helps me to better analyse the problems.	Lee *et al*. (2010)
Comparison with conventional training methods	1. I found this simulation more engaging than conventional training methods (like fire drills, non-interactive videos, health and safety inductions, recommendation leaflets, and seminars). 2. It was easy to remember the recommendations provided in this simulation compared with those provided during conventional training sessions. 3. I prefer fire safety training that uses this simulation over conventional training tools.	Lovreglio *et al*. (2020)