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Report 3218

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Abstract. A forensic investigation of a fire scene can provide insights on the circumstances of a fatal fire. However, people's attitudes and subsequent behaviour can only be inferred. A full reconstruction in real life of a fatal fire is generally not possible due to ethical reasons regarding the serious threat people would be exposed to and the costs that such an experiment would have. We propose here the ForensicVR method, a novel and innovative way to study human behaviour in fire by recreating, in Virtual Reality (VR), evacuation scenarios from real-world, well-documented fatal fires. The methodology has been developed and tested for two case studies, namely 1) a hotel fire scenario, in which the behaviour of individuals in their rooms was investigated and 2) a nightclub fire scenario, in which the impact of social influence on evacuation behaviour have been studied. Two set of VR evacuation experiments have been conducted for these case studies, including a total of 122 participants. Results show that participants in a VR experiment attempt and succeed at performing both simple and complex actions when exposed to a fire evacuation scenario. Participants reported some level of stress due to the simulated emergency, despite knowing the threat was not real. Participants in the scenario behaved in a comparable way as the victims of the corresponding real fires, which supports the potential of the ForensicVR methodology.

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1. Introduction

Fire incidents can have serious consequences on life safety, including cases with high number of fatalities (Rahim, 2015). Forensic investigations are conducted in case of fatal fires to obtain information about both physical and human factors which affected their outcome. Physical factors concern the characteristics of the environment and their possible impact on the fire ignition and development (e.g. available fire extinguishment means, geometrical configuration of the compartments, installations, etc.). Human factors relate to the actions of both emergency responders as well as the victims who were exposed to the hazard. In this context, the decision making of the evacuees can play a fundamental role on the outcome of a fire, i.e., they may lead to a greater or lower number of fatalities. After every fatal fire, forensic fire investigators wonder indeed how people perceived the situation and what factors have influenced their behaviour.

Understanding human behaviour in case of fire evacuation is a complex multi-disciplinary subject which has been investigated for several years adopting a variety of theories and models (Kobes et al., 2010). The collection of data on human behaviour in fire emergencies can be particularly challenging for a variety of reasons. The witnesses as well as the fatal victims may have not been in the same location, they may have had different available information and they may even have had different perspectives before and during the course of the event. In addition, regardless of the presence and severity of physical injuries, fire survivors may have post-traumatic stress symptoms (Schneider et al., 2012). Reconstruction of the events can also be linked to cognitive or memory biases (Uhr et al., 2016).

Fatal fires are usually thoroughly investigated, but due to their nature, it is often possible to collect information mostly about the result of an evacuation, not the process itself. Forensic fire investigators rely often on crucial information provided by the survivor's accounts. Nevertheless, different types of voluntary, involuntary and subconscious issues may be associated with memory, including memory conformity, misinformation effect, biases, false memories, etc. (Wickens and Hollands, 2000; Wright et al., 2009; Wright and Loftus, 1998). Memory errors may therefore affect the accuracy of the information provided, thus decreasing the reliability of the information provided. These issues lead to the identification of the need for additional tools able to inform forensic fire investigators. Such tools could be used in parallel with the accounts of witnesses in order to complement, question or confirm the findings based on such information.

This project focused on the development of a new methodology to perform fire evacuation investigators aimed at studying human behaviour in fire, the ForensicVR methodology. Virtual Reality (VR) is a relatively novel methodology for the study of fire evacuation (Kinateder et al., 2014b). Several VR technologies are available for the conduction of VR experiments, including CAVE Automatic Virtual Environments (Juan and Pérez, 2009; Ronchi et al., 2016), Head Mounted displays (HMD) (Cosma et al., 2016), head mounted display powered by mobile-phones (Mayorga, 2017), etc. Previous research has shown that VR has a great potential to be a valid alternative to traditional laboratory experiments with the advantage to allow for high-experimental control, reduced ethical issues and cost-effectiveness (Andrée et al., 2016; Cosma et al., 2016; Duarte et al., 2010; Kinateder, 2013; Kinateder et al., 2014a; Ribeiro et al., 2012; Ronchi et al., 2015). Therefore, a virtual representation of a fire evacuation scenario is a valuable option to obtain insights on the behaviours of people experiencing such scenarios.

1.1. Aim and objectives

The overall aim of this work is to present a first approach to the ForensicVR method. The ForensicVR method is developed and evaluated performing the reconstruction of two well-documented fire evacuation events in Virtual Reality, in order to be able to provide a scenario in which it is possible to investigate the behaviours that people may have in a situation which resemble the actual fire. The behaviours of people in VR are observed and then compared to the ones documented in the actual fire investigation reports. ForensicVR is a new method for forensic investigations which aims at providing an increased understanding of the decisions of the victims and their impact on the outcome. By analysing the subjects' attitudes and behaviours in the virtual environment, such as decision-making, exit choice, and sequence of actions performed, it is possible to collect data and information that can be a game changer in a forensic investigation. The objective of the work is therefore to provide a comparison between human behaviour in VR and in the real world which allows an evaluation of the potential of the ForensicVR method. In addition, this study aims to further support the existing research on the use of VR as a tool to investigate human behaviour in fire.

1.2. Report overview

This report presents the findings of two sets of experiments, which have been conducted to develop and evaluate the ForensicVR methodology. These experiments have been designed in order to consider two types of scenarios that may occur during a fire, namely 1) decision making of an evacuee in isolation (i.e. a person who needs to decide alone), and 2) decision making given the presence of social influence (Kinateder et al., 2014a; Kinateder and Warren, 2016).

The report structure is here presented. The first chapter introduces the ForensicVR project (chapter I: Introduction) and the overall objectives of the project. Chapter II (Method) introduces the use of Virtual Reality and how this is applied in the context of the ForensicVR methodology. Chapter III (The evacuation experiments) presents the set of experiments (individual behaviour and social influence) which have been conducted to develop and evaluate the ForensicVR methodology. Chapter IV (Discussion) provides a critical analysis of the results of the experiments in light of existing research, as well as the limitations of the current work and the needed future research directions. Chapter V (Conclusion) presents a final set of considerations concerning the ForensicVR methodology.

2. Method

The development and evaluation of the ForensicVR methodology relies on the use of Virtual Reality (VR). VR has been previously applied in the context of fire evacuation research in a variety of contexts and applications. This includes its use for both applied and fundamental research. For instance, VR has been used for training purposes (Lovreglio et al., 2017; Williams-Bell et al., 2014), evaluation of the effectiveness of way-finding systems (Cosma et al., 2016; Ronchi et al., 2016) or to uncover the fundamental variables which affect decision making (Andrée et al., 2016; Kinateder, 2013; Kinateder et al., 2014a, 2013; Kinateder and Warren, 2016; Moussaïd et al., 2016; Ren et al., 2008; Rio and Warren, 2014).

In order to develop and provide an initial validation of the ForensicVR method, a first step consisted in the comparison between the behaviours which have been observed in a real fire scenario and those observed in VR. To do so, two well-documented fire evacuation scenarios have been identified by performing a literature review of real-world fires. The criteria for the selection of the real fire scenarios included 1) depth of the information available concerning survivor accounts, 2) depth of the information available concerning the fire scene, i.e. the environment and the fire/smoke development, 3) a significant number of fatalities have occurred in the fire, 4) the environment has a level of sophistication and clutter that can be reasonably represented in VR with a sufficient degree of accuracy given the scope of the work.

Two fire evacuation cases to reconstruct in VR were identified, namely 1) a fatal fire involving an individual evacuation (i.e. an individual in a hotel) and 2) a fatal fire involving the evacuation of a person in a crowded scene. These two cases have been selected because - besides the number of occupants – it is necessary to evaluate the ForensicVR methodology for both the case of individual behaviour (used as benchmark to evaluate to which extent it is possible to observe individual actions which are comparable to real life) as well as social influence (which has been identified as one of the key factors affecting human behaviour in fire emergency situations (Kinateder, 2013). The individual evacuation scenario aims at isolating the individual's response to the fire event. The group evacuation scenario aims at studying the effect of other people's behaviour on the attitudes and behaviour of the subjects. In both scenarios, the fire threat is located in the same location as in the real case and the participants are given a similar initial conditions as the real case (e.g., presence of other people, presence of smoke and its movement, etc.).

Based on these criteria, two well-documented fires have been identified:

1) Individual behaviour scenario: The MGM Grand Hotel Fire in 1980 (Best and Demers, 1982)
2) Social influence scenario: The Stardust nightclub fire in 1981 (Coffey, 2009; Cosgrove, 2016; Keane, 1982; Woolley et al., 1984)

These two fires presented all characteristics needed for the scope of the work. In addition, they are often referred in the fire evacuation literature as "classic" case studies, which have been used over the years as case studies to investigate human behaviour in fire (Bryan, 1983; Canter, 1990).

A brief summary of the events during the fires is reported here. The key information necessary for the development and understanding of the VR scenario is here reported. More detailed information about the fire events can be found in the official investigation reports published after the fires as well as further independent examinations (Best and Demers, 1982; Bryan, 1983; Coffey, 2009; Keane, 1982; Woolley et al., 1984),

Experiment 1: The MGM Grand Hotel Fire
The MGM Grand hotel fire took place in a casino at 7.00 am on November 21st 1980. A faulty electrical connection was identified as the cause of the fire. The fire started in the deli area of the casino and then he rapidly spread and engulfed the whole casino. No sprinkler system was installed in the facility as it was not required by the regulations at the time given the type of occupation of the building. The smoke spread reached up to the 26th floor of the hotel through the seismic joints, the staircases and the elevators shafts. The time at which the fire occurred (early morning) had an impact on the behaviour of the occupants, as many hotel guests were asleep or in bed. This means that many of them found out about the fire only after the smoke entered their rooms. Since the smoke ascended through the staircases, many of them were not available for evacuation (it should be noted though that the smoke conditions varied among the staircases). The presence of the smoke in the hallway among with its conditions (e.g., reduced visibility, presence of irritants, etc.) made it difficult for the hotel guests to leave their rooms, thus many of them were forced back in their attempts to evacuate. As consequence, many occupants remained trapped in their room. Their actions in the room included efforts to manage the smoke until they were rescued by the fire and emergency service personnel. The time spent in the room by hotel guests reached even the order of magnitude of hours. A total of 85 people died in the fire among a population which has been estimated to be in the order of 5,000 people.

After the fire, extensive investigations took place in order to reconstruct the course of the events. The National Fire Protection Association (NFPA) submitted a mailed survey which aimed at collecting data on the survivors' experience of the fire. Such behavioural data have been then compiled and analysed (Bryan, 1983).

Experiment 2: The Stardust nightclub fire
The Stardust nightclub fire started early in the morning of February 14th, 1981. The Stardust nightclub was located in the north of Dublin, Ireland. The origin of the fire has been traced to the West Alcove, which was not available to the public that night, behind blinds. There were no automatic fire detectors. According to the Report of the Tribunal of inquiry, eye-witnesses gave different accounts on the precise location and size of the fire at the time it was discovered. However, once it was detected either by seeing flames behind the blinds, by smelling or seeing smoke, or by feeling a rise of temperature near the West Alcove, the staff attempted unsuccessfully to extinguish it. Although calls to the fire brigade were made, the music kept playing for roughly 4 minutes from the moment flames were visible. Then, disc jockey stopped the music and made an announcement to indicate people to evacuate the premises. By that time, however, the flames were already at ceiling level, having taken over the entire West Alcove. Within the next minutes the flames reached the ceiling in the ballroom, the ceiling started to collapse. Many patrons deliberately ignored the message, according to the investigation, and remained in the ballroom to observe the fire. Some of the emergency exits were locked, as it was a common practice to prevent patrons from accessing the building without paying. This issue combined with a fast growing fire and a delayed evacuation are believed to have played a role in the high number of fatalities and injuries. The Stardust nightclub fire took the life of 48 people, severely injuring other 128. Most of the victims were young people.

After the fire, a Tribunal was constituted to investigate the fire. The report produced by that Tribunal in 1982 (Keane, 1982) was used in this study for collecting data on the behaviour of the patrons during the fire.

3. The evacuation experiments

This chapter describes the evacuation experiments which have been conducted for the development and evaluation of the ForensicVR methodology. The experiments took place in different sessions among 2018. The Individual Behaviour experiment (hotel scenario, experiment 1) took place during the spring, between May and June 2018, while the Social influence experiment (nightclub scenario, experiment 2) were conducted during September 2018.

The two sets of evacuation experiments are here presented including:
1) The description of the sample of participants who took place in the experiments,
2) The VR equipment which has been used to build the VR scenarios and conduct the experiments,
3) The simulated environment which has been reproduced in VR,
4) The experimental procedure,
5) The scenarios which have been investigated,
6) The results of the experiments

The following sections describe these aspects in more detail.

3.1. Participants

The characteristics of the participants who took part in the two sets of experiments are presented here.

Experiment 1: Individual behaviour

Data from a total of 55 participants were obtained for this scenario. It should be noted that the data from additional 15 participants had to be removed from the sample due to a technical problem. The sample included 32 male, 21 female, 1 non-binary and 1 preferred not to say. The age of the participants was between 18 and 53 years old, with an average of 26.6 years and a standard deviation of 7.6 years old (mode=21 years old). Participants were also asked if they got fire safety training and the result was that 34% of the participants claimed they have not got any.

The VR sample was later be compared to the sample of the victims of the MGM Grand fire, the "real" sample. This real sample consisted of the answers from 118 NFPA surveys. Ideally the real sample would consist of victims completely on their own, but only 20 cases were identified as such. Therefore, 98 responses of occupants that stated they were with their spouse or a relative were included in the sample. In 24 cases, each of the two occupants of a given room submitted a reply each (a total of 48 replies), while the remaining 50 were submitted by only one of the two occupants. The real sample consisted of 76 males and 42 females. The maximum age was 84 and the minimum 20, with an average of 46.4, a standard deviation of 12, and a mode of 50. It was assumed that, given the limited possible actions to perform, the behaviour of a single occupant or a group would not differ much. However, some groups were large (more than 10 people), and were a result of strangers helping each other, allowing people into the room at different times along their waiting period. The consequence was that some members of the group may have arrived once certain actions were already performed, and therefore they may reply "no" in the survey because it was done already. In some cases, people abandoned the group in their attempt of evacuating the building. Alternatively, a couple or two relatives would have stronger bonds, and remain together throughout the experience. In addition, having both people been together in the room before noticing the emergency, it is likely that both of them were there while each action was performed, even if they did not did it themselves but it was done by the other member of the pair.

Experiment 2: Social influence
A total of 67 people participated in this scenario. The sample consisted of 30 males, 36 females, and 1 non-binary participant. The age of the participants ranged between 18 and 42, with an average of 26.2 and a standard deviation of 5.3 years (mode=23 years old). When asked if they got fire safety training, 58.0% of the participants said yes. The rest claimed not to have got any.

3.2. Equipment

The equipment in use in both experiments consisted in the use of the HMD technology (HTC Vive™, dual AMOLED 3.6" diagonal screen, 90 Hz refresh rate and 110 degrees of field of view, 1080x1200 pixels per eye, and 6 degrees of freedom of movement) to display the virtual environments.

A high-end computer (Intel i7 7700k CPU) was used to run the scenarios with the HMD device; this included an Nvidia GeForce GTX 1080 8GB GPU and 32 GB of RAM. The computer was able to keep a locked framerate of 90 frames per second or higher throughout the whole duration of the experiments. This was tested to ensure that there were no inconsistencies between the movement of the participants and the rendered images. The virtual environments were built using the 3D modelling tool SketchUp™ and the Unity3D™ game engine.

Experiment 1: Individual Behaviour
A wireless solution (TPCast wireless adaptor for HTC Vive) was mounted to the HMD in order to allow participants to walk around in the physical environment in the same way as in the virtual environment. This was made using a wireless connection. The base stations of the HTC Vive which allows tracking of the position and rotation of the HMD need to be place at a maximum distance of 5 m apart from each other. As the hotel room in the study had a maximum length of one side of the room of about 5.6 m, the base stations were placed at maximum distance in order to take full advantage of the area coverage. This yielded an area of 4x4 m^2 in which participants could physically move and have their movement tracked (see Figure 1).

Figure 1. Lab space in which the VR experiments took place.

The experimental room in which the experiment took place consisted of a room with a clear space of approximately 5x5 m^2. This allowed to include a buffer zone of 0.5 m to the nearest wall or furniture, i.e. in this manner, participants would not interact with any physical obstacles during their movement in VR. The HMD equipment allowed to show participants the boundaries of the available space if they get too close to the edges of the scenario. Once approximately half of the experiments have been conducted, the wireless solution had a technical fault, thus it was replaced with the original HTC Vive cable. The cable had a length of 4 m, thus it still allowed the participants to freely move in the virtual environment.

While movement took place freely in the physical environment matching the size of the virtual environment, the HTC hand controllers were used to interact with the objects in the hotel room.

Experiment 2: Social influence
Given the large area of a nightclub, much larger than that covered by the VR equipment used in this study, it was not possible to use the wireless solution so that the participants could walk freely on an empty space. Participants were therefore standing only (although they could around or spin in the physical environment) and the chosen navigation method for the VR nightclub scenario was the hand controllers.

3.3. Environment

This section presents a description of the environments in the virtual experiments.

Experiment 1: Individual Behaviour
The room selected for this experiment was a generic hotel room (see Figure 2). The 3D hotel room model fit the requirements of the experimental design (e.g. the layout corresponded to the available experimental area). The hotel room consisted of a bedroom and a bathroom. The decorations and furnishing were selected in order to minimize interactions with irrelevant objects. When possible, it was therefore chosen to have built-in furniture (e.g. the desk, the spotlights and diffused lights instead of lamps) as they would reduce the time participants could spend interacting with such objects.

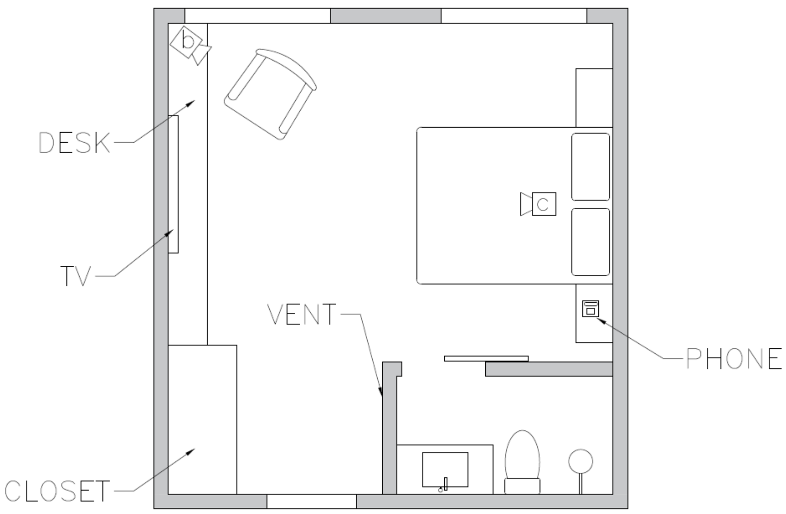

Figure 2. Layout of the VR hotel room and location of the cameras use for Figure 3. The walkable area is around 4x4 m2. Figure not on scale

The main elements which were in the room included (see Figure 2), a double bed with four pillows and built-in nightstands, a corded phone within one of the built-in nightstands, an armchair, a built-in desk, a closet, a TV fixed to the wall and the TV remote controller. The remote controller could turn the TV on and off, and change between three different channels, showing random, irrelevant mute videos. A sliding door separated the bedroom from the bathroom.
The decorations in the room consisted of two paintings and a statuette.

Figure 3. A screenshot from the VR environment of the hotel room.

The main elements in the bathroom included a sink, a working faucet, a shelf with three rolled towels, a toilet, a working shower, toiletries and a wastebasket. Both bedroom and bathroom had working light switches that would turn on and off the lights.

The room also had two casement windows, each with two casements, which could be opened independently. Before the smoke entered the room, participants could open the windows and hear wind and traffic noises coming from outside. Once the smoke was activated, those sounds would be replaced by fire truck sirens and the sound of a helicopter. Participants could only hear those sounds, they could not see any rescue vehicles or people outside. The view from the windows was a 360 degree night view of Las Vegas, probably taken from a helicopter, which gave the impression of being in a high-rise building.

The full list of objects in the hotel room and the possible interactions with the participant are presented in Table 1. The interactions with the objects in the room were designed in order to be as realistic as possible. For this reason and due to computational constraints, certain room features have been removed from the environment as they would give a lower level of realism in VR. An example is the lack of curtains in the room, as it would be expensive in computational terms to convey the natural movement of a fabric when pulled or pushed. If the material would not behave as the participant expected it to do, the realism of the room would be affected negatively. Therefore, the chosen solution was to eliminate as many fabric or cloth-like materials as possible, which was a relatively easy task in the case of curtains. The curtains were absent but a switch on the wall between the two windows would activate an electric glass system that fogs up the glass. This is an existing system currently used for privacy in offices with glass doors and walls. The towels in the bathroom were rolled up in a cylinder, and would maintain that shape. It was not possible to unwind them, so participants would have to use them as a solid material.

Table 1. Objects in the hotel room and possible interactions with the participants.

item	movable	player interaction
chair	yes	pick up and move around
statuette	yes	pick up and move around
notepad	yes	pick up and move around
speakers	yes	pick up and move around
toiletries	yes	pick up and move around
pillows	yes	pick up and move around, get wet, block vent
rolled towels	yes	pick up and move around, get wet, block vent
paper bin	yes	pick up and move around, get wet, block vent
corded telephone	yes	pick up and move round, give dial tone and dead line tone when held near ear
TV remote	yes	turn TV on/off, change channels
toilet	partially	lift and lower lid and seat, flush (sound only)
windows	partially	open and close casements
room door	partially	open and close swing door
closet	partially	open and close two independent swing doors
desk cabinet	partially	open and close two independent swing doors
sink faucet	partially	open and close, use water stream to wet material
bathroom door	partially	slide open or close
shower	partially	open and close, use water stream to wet material
desk	no	place objects on top of it
bed	no	place objects on top of it
bathroom sink	no	place objects on top of it
vent	no	put dry and/or wet materials on to block it
light switch	no	turn on/off lights in room
TV	no	turn on/off, change channels (see TV remote)

A video of the hotel room is available at the following link:
https://www.youtube.com/watch?v=apwKutZp6ds&feature=youtu.be

Experiment 2: Social influence

For the social influence experiment, a nightclub similar to the original Stardust nightclub was produced in 3D. The dimensions and general outlook of the nightclub were taken from various publicly available sources (Brackside Merlin Films, 2006; Cosgrove, 2016; Tribunal of inquiry of the fire at the Stardust - Artane - Dublin on the 14th February - 1981 & Keane, 1982). The layout of the scenario can be seen on Figure 4.

The VR nightclub resembled in general the ballroom and the West Alcove from the original Stardust nightclub. The furnishings (i.e. seating areas and furnishing in the west alcove) were also placed similarly. There were around 250 computer-generated patrons (avatars) in the nightclub. They were sitting at the tables or standing around the ballroom. These avatars were animated, and imitating reality, they were in groups, gesturing as they were talking to each other. Some of them were dancing on the dance floor. The avatars were not able to interact with the participant, but they were animated to appear to interact with each other, and ignored any attempt of interaction from the participant. A bartender was at the bar, on which some glasses of beer were available for the participant to grab. Being a nightclub, there were no more objects for the participant to pick up and interact with.

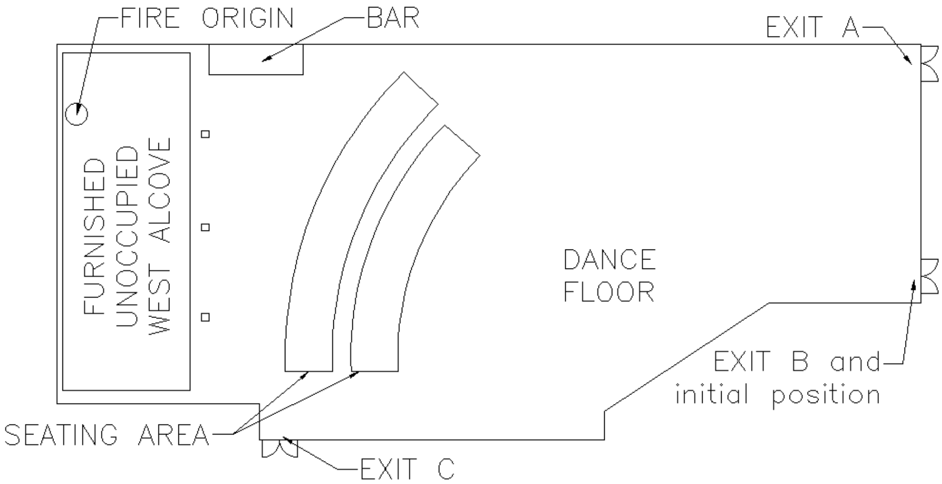

Figure 4. Layout of the VR nightclub, based on the original layout of the Stardust nightclub. Exit C was the main entrance of the nightclub.

The West Alcove in the VR scenario was fully furnished with chairs and tables similar to the ones on the seating area in the ballroom, based on the kind of furniture used in the real nightclub. No occupants were in the West Alcove when the scenario started. There was no wall or blinds separating the West Alcove from the ballroom, contrary to the case of the real nightclub, in order to give full visibility of the flames to the participant. This aimed to compensate for the lack of smell of smoke in VR compared to the real fire. However, in the VR scenario the West Alcove was kept unlit, completely in the dark, until the fire started.

All exits had a luminous sign marking them as an emergency exit. They were also equipped with opening device, so-called "panic bars". Through the illumination, emphasis was made on them to be visible to the participants, since they only had a couple of minutes to explore the scenario, compared to the few hours a person spends in a nightclub, even if being there for the first time.

3.4. Procedure

Prior conducting the experiments, an ethical assessment was made according to the routines at the Division of Fire Safety Engineering at Lund University. Contact was made with the Swedish Ethical Board in order to get approval for VR evacuation experiments conducted at the division and they concluded that a full application was not necessary given the limited risks of the experiments, thus ethical permission was obtained to perform VR evacuation experiments. The recruitment of the participants was made in both experiments using a specialized recruiting website which is commonly used at Swedish Universities. The participants received a compensation equal to two cinema tickets to take part in the experiments. The call for participation in the experiments referred to a "highly realistic scenario". People could volunteer to take part in the experiments and they will receive more detailed information once they signed up. No reference was made about a fire or an emergency in the information provided. This was done in order to not influence their behaviour during the experiments. Participants received an informed consent form, which they were asked to read before coming to the experiments. The informed consent form was available upon arrival to the experimental room so that participants could sign it. Participants chose a time slot in which they could perform the experiments in a schedule. Therefore, participants arrived one at a time at the designated place and time for the experiments.

Once a participant arrived on the site of the experiments, s/he was guided to the experimental room. There he was asked to sign the informed consent form. After signing the form, it was given a brief introduction about the equipment and the navigation method. Then the researcher helped the participant to wear the HMD equipment (as well as the VR wireless solution and battery pack, in the cases in which they were used) as well as the hand controllers to hold. Once the participant had all equipment installed comfortably on himself, a training scenario was initiated by the researcher. A training session (without anything indicating fire or emergency) was the given to participants before the actual experiments in order to get the familiar with the hand controllers. The scope was to have them learning how to pick up objects, navigate or operate other interactions in the VR scenario before the start of the experiments.

After the training scenario was completed, the participants were informed that they could withdraw from the experiment at any time for any reason and that they only needed to tell this to the research present in the room. Having clarified that and any other questions the participants had, the corresponding scenario was launched.

The actual experiment then took place (see below for further information about the experimental procedure in both experiments). During the navigation of participants in the room and their interactions with objects, their movement and behaviour were followed on a computer screen by a researcher. These were also recorded on video. Once the experiment was terminated, the participant would be asked to remove the equipment, and it was guided to fill out a questionnaire. After he/she responded to the questionnaire, the researcher performed an interview asking if some unusual behaviour was observed. Questions and answers were recorded. A final debriefing consisted in the explanation of the aim of the study, the fact that the scenario was based on a real-world fire scenario, and how the data would be used. The participant was then given the opportunity to ask further questions. Finally, the participant received its compensation (two cinema tickets) and was guided out of the experimental room.

Experiment 1: Individual Behaviour

When the hotel room experiment on individual behaviour started, participants were told to listen to a set of instructions. The instructions told them that they were in their hotel room where they just checked in and that they were going to spend the night there. Other information given to participants included a statement that the room was highly realistic and that it could feel like a real room. Then, they were asked to explore the room and the objects therein, as well as try interacting with the objects in the room as they would do in reality. They were told that this was made to test how realistic it felt to interact with the objects in the room. They were also told that they could make comments during the experiments, and that they would be asked after the experiments to write down their experience in a post-experiment questionnaire. They were asked if they had any further questions and after getting a reply, they were told that would not receive any further instructions and the experiment was starting.

Once the researcher assessed that the participant had finished the exploration of the room and its objects, the smoke was manually activated. The smoke will come in the room from a vent next to the main door and will start spilling into the room. After the activation of the smoke, participants realized at some point that smoke was present in the room by seeing the plume and/or the smoke layer piling on the ceiling and they behaved as they considered appropriate in such circumstances. Their actions were then recorded and the researcher noted the times at which 1) the smoke was triggered, 2) the participants unequivocally saw the smoke and 2) the experiment was stopped (and why).

Experiment 2: Social influence

In the case of the nightclub experiment on social influence, the participant was in a crowded scene (see Figure 5) and it was given instructions before the scenario started, to prevent the loud music to make it difficult for them to hear the message. The instructions said that they were in a nightclub, they had just arrived, and that they were supposed to test its realism. In order to do that, they were told they could walk around and explore it as they would do in a real nightclub, and that they could grab a drink at the bar. They were also told that they could make comments during the experiments, and that they would be asked after the experiments to write down their experience in a post-experiment questionnaire. They were asked if they had any further questions and after getting a reply, they were told that would not receive any further instructions and the experiment was starting.

Figure 5. Screenshot from the initial position of the participant in the virtual environment, i.e., the nightclub fire. The figure brightness is here increased to make the scene more clearly visible.

Once the researcher assessed that the participant was done exploring the scenario, he/she manually activated the fire so that flames were visible in the West Alcove. The fire growth of the fire was manually paused until the participant noticed it and approached it. Only then the fire was allowed to grow in a predefined rate, matching in general the description provided in the Report of the Tribunal (Keane, 1982).

Figure 6. View of the initial stages of the fire as seen from the distance. The figure brightness is here increased to make the scene more clearly visible.

When the participant was near the fire, some of the avatars in its vicinity approached the West Alcove and stood there observing the fire (see Figure 6). After a couple of seconds, the bartender stepped in, carrying an extinguisher, and aimed at the fire. During this extinguishing attempt, another avatar stepped in also equipped with an extinguisher and did the same (see Figure 7). Both of them failed to extinguish the fire, and walked away. The onlookers walked away too, towards the exits. A few seconds later, having the fire growth considerably, suddenly the music stopped playing, and a male voice (the disk jockey) made a loud and clear announcement, as stated in the Report: "We have a slight problem, don't panic. Walk to the nearest exits". By that time there were no onlookers around the fire anymore, but the rest of the avatars were still interacting with each other as in the beginning. The fire only grew within the limits of the West Alcove, never expanding into the ballroom.

Figure 7. Extinguishing attempt by one of the members of the staff in the virtual environment. The figure brightness is here increased to make the scene more clearly visible.

The behaviour of the participants was followed on a computer screen by a researcher, and it was recorded on video. Notes were made on when the participant approached any emergency exit, and which exit it was. The behaviour of the avatars was overall similar to what was described in the fire investigation report (i.e. the main behaviours were represented such as the fire extinguishment attempts, the people approaching the fire and the announcement of DJ).

3.5. Scenarios

The two sets of experiments were conducted considering different scenarios focusing on the individual actions performed while alone (experiment 1) and in presence of other people (scenario 2).

Experiment 1: Individual Behaviour

During the experiments, the participants were not aware that they had only few actions they could perform. These actions were designed in order to match those described by the survivors of the actual fire in the NFPA survey. The actions included:

- *Exit the room*: when a participant tried to open the main room door, they encountered a hallway filled with smoke. If the participant would still try to go out, the researcher said out loud "outside is worse", which reflected what the victims assessed in the actual fire. In the unusual case of a participant still trying to walk into the hallway, the researcher stopped the experiment immediately, since people leaving the room was out of the scope of the study.

- *Use the telephone*: a telephone was available, but once the smoke was triggered, the line went out of order.
- *Look for news on the TV*: the different channels on the TV kept showing the same programs as before the smoke was triggered.
- *Manage the smoke*: open windows, block the vent.
- *Try to signal their presence to the rescue services (wave arms or objects by the window)*: participants could try to signal to the helicopter or the firefighters. However, it was not possible for them to see neither of them. Nevertheless, their attempt was identified by them waving at the window, calling for help out loud, or waving objects at the window.

Blocking the vent from which the smoke was coming into the room was possibly by using any object that the participant could pick up in the room. The faucet of the sink and the shower could be used to wet an object. Once an object would get wet with water, its colour would rapidly change into a darker shade to indicate the wetness. The entire object would get wet at the same time, regardless of the location in which it was exposed to the water stream. The participants could then opt for putting wet or dry objects in front of the vent in an attempt to block the smoke. To prevent completely the smoke to come into the room through the vent, the participant needed a single wet object or two dry objects. In case a single dry object was used, it would reduce the inflow of the smoke plume significantly, although it would not stop it fully.

The smoke layer would continue to fill in the room with smoke if the participant failed to block the vent where it came in. The visibility would therefore reduce, as the smoke layer would keep going down until it reaches the floor. From the moment of activation, the smoke took 6 minutes and 15 seconds to reach the floor. The participant could still see around himself with a visibility of approximately 1 m of distance or lower. This was based on the assumption that a person in pitch-black smoke could still touch and feel the objects around him/her and operate them. This might not be necessary the case in real life, as it would depend on the density of the smoke, the lighting conditions in the room and the smoke irritants. Since the sense of touch was not included in the VR experiment, the minimum 1 m visibility was chosen as a reasonable compensation.

Another option for the participants to remove the smoke from the room was to open the windows. Both windows could be open and they had two independent casements hinged vertically on the sides. The smoke clearing would depend on both the number of open casements as well as the opening angle of each of them. In addition, participants who would fail to shut the main door after a failed attempt to escape would get their room filled with smoke also from the hallway. This was represented by having a smoke layer coming down faster than in the case when the door was closed. This assumption was made as it was in line with the actual accounts of the survivors of the fire.

Each experiment was stopped once the research would observe three types of behaviour, namely:

1) A participant not doing anything about attempting blocking the smoke
2) A participant repeating unsuccessfully the same action or actions constantly
3) A participant who had managed to block the smoke and would not do any other action

These three sets of behaviour would lead to consider that there are no relevant data anymore to collect, thus the experiment could be interrupted. This was designed in order to match the description of the actions of the actual fire victims, as in some instances they had nothing else to do apart from waiting for being rescued.

For example, the experiment was interrupted in case the smoke layer reached the floor and the participant had not made any attempt to block the vent or opening the windows, it was assumed that no further attempts would be made to manage the smoke. The second situation occurred when for instance a participant who tried unsuccessfully to use the telephone for over a minute. The third case referred to a participant who managed to block the smoke and did all or most other possible actions/interactions in the scenario and then stood still, waiting for something else to happen.

Experiment 2: Social influence

In the nightclub scenario, the participants were not aware of the possible actions they could perform, but they could not do anything but leaving. There were no manual call points for the alarms, there were no fire hoses or other extinguishers they could use. The only choice they had, therefore, was to leave. Different *key moments* were identified that could serve as cues to the participants about the need to evacuate the building:

- *After seeing the flames*: the participants may see the fire from the distance, but it was not considered it was noticed until they approached it and inspected it long enough to realize that it was a fire and not some other kind of controlled combustion (e.g. a fireplace).
- *After watching extinguishing attempts*: the participants that did not leave after the first key moment were able to see two members of the staff attempting to extinguish the fire. Those participants witnessed both extinguishing attempts fail, and could therefore decide it was time to evacuate.
- *After seeing onlookers leave*: after the staff failed at extinguishing the fire, onlookers that gathered around it walked away, towards the emergency exits and left the building. The participants who did not leave after the previous key moment could decide to follow them.
- *After the disc jockey made the announcement:* lastly, the disc jockey stopped the music and made a clear announcement asking people to walk towards the exits. The participants who did not evacuate after the previous key moment could decide to follow this advice and leave the premises.
- *Do not leave:* some participants may decide there is no need to evacuate and remain in the building despite the above-mentioned key moments.

It should be noticed that these key moments took place in a sequence, which means that for one to occur, the previous ones should have occurred already. Therefore, a participant deciding to leave after the disc jockey made the announcement had already noticed the fire, watched the extinguishing attempts and seen the onlookers walk away. Therefore, the decision-making of that participant cannot be attributed to that single key moment, but to the sum of those that took place before starting the evacuation.

The experiment was stopped once the participant reached one of the emergency exits or at least a minute after the disc jockey made the announcement, since after that point in the real fire there were also people ignoring the message.

All participants were exposed to the same scenario, although approximately half of them were told that in the nightclub there may or may not be another participant connected from a remote laboratory (a multi-player VR experience). The goal was to explore if the simulated virtual presence of another human being would change the behaviour of the participant in the VR scenario. In reality there was no remote laboratory and no other participants in the VR nightclub, therefore the scenario was strictly the same for all participants, but this allowed to separate the participants in two samples, as shown in Table 2.

Table 2. Samples and their sizes in the group behaviour experiment.

Sample	Participants
Single-player	34
Multi-player	33

3.6. Results

This section presents the results from the two sets of experiments. The types of results differ in some instances between the two experiments, given the different nature of the scenarios (person alone vs presence of other people) and the research questions investigated (how people behave alone vs social influence).

Experiment 1: Individual Behaviour

The analysis of the results of experiment 1 focused on the assessment of the actions performed by participants in the hotel room. This included the comparison between the actions performed in VR and those performed in the real fire scenario. It is important to note that participants were neither instructed on which actions to take, nor they knew the scope of the experiment.

3.6.1. Experiment 1: Actions performed

The actions which were observed to match between the VR and the actual scenarios were:

1) Attempting to manage/block the smoke
2) Trying to use the telephone
3) Turning on the television to look for information
4) Signalling their presence to the rescue services

The participants also reported their stress levels during the simulated fire emergency as well as they were asked to provide an evaluation about the realism of the scenario.

The possible actions of the participants along with their overall performance in VR is compared with the behaviour of the victims of the MGM Grand fire. This comparison is presented in Figure 8 and it compares the VR sample vs the real sample. The behaviours of the VR sample were counted assuming that the actions would be representative if performed after they saw the smoke plum spilling into the room.

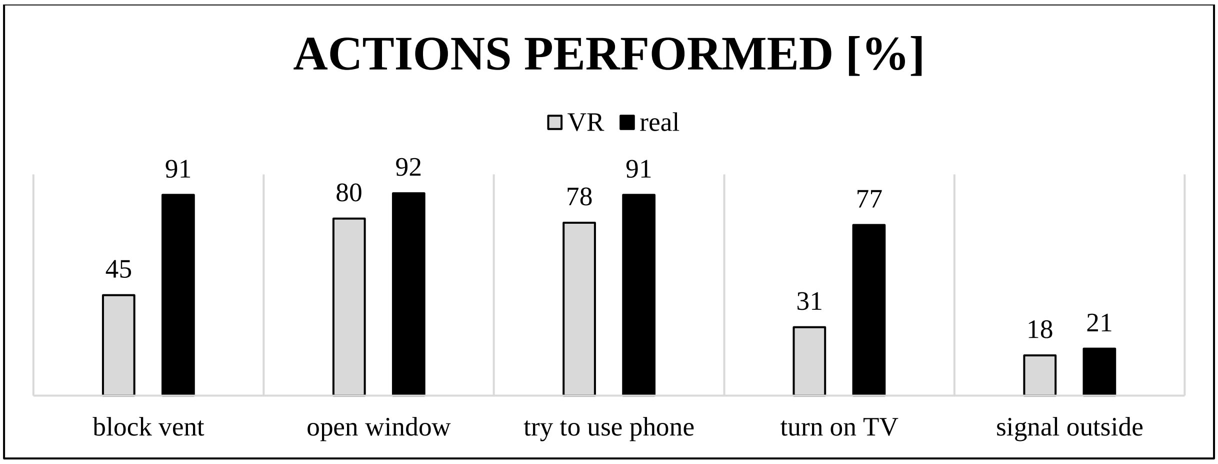

Figure 8. Percentages of the VR and the real sample successfully performing an action, based on a total of 55 participants.

All possible actions were performed by participants, although the frequency in which they were performed varied. A closer match was observed for the actions “open windows”, “use phone”, and signal outside”. In the other actions, the difference in frequency was at least 50% between the two samples.

For instance, while 45% of the VR sample blocked the vent, 80% of them opened one or more windows to manage the smoke. Approximately 74% of the participants attempted to use the corded telephone. Despite their attempt to use the telephone appeared evident, it was not possible to evaluate if the call was towards the rescue services or the front desk (as the victims did).

The number of actions (out of the 5 possible ones) which were performed by the participants was also counted, in order to provide insights into the number of participants attempting more than one realistic action (see Figure 9).

It can be noted that on average, participants performed 2.56 actions each (mode 3 and standard deviation 1.36). Only 4 participants (approximately 7%) performed no actions, and the same number of participants performed all five actions.

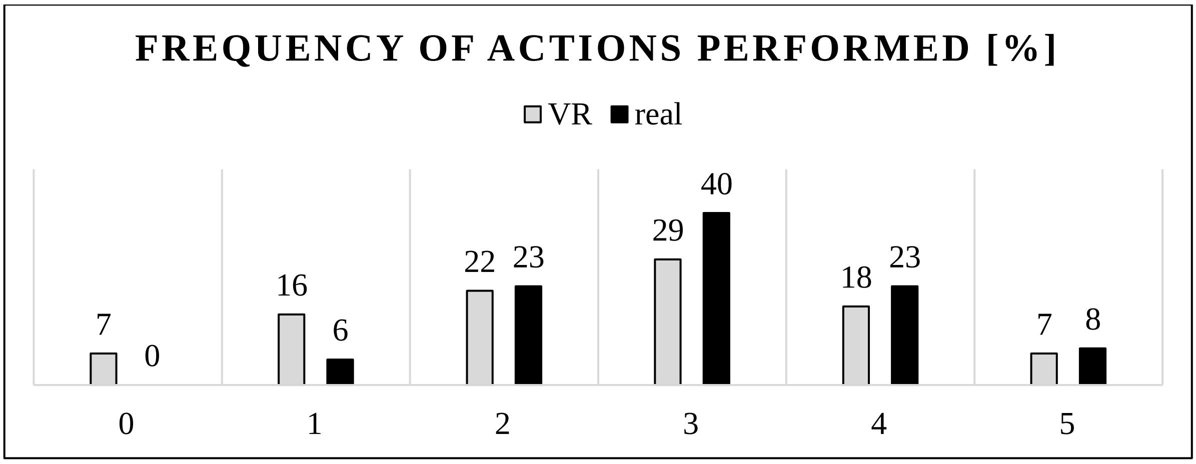

Figure 9. Percentage of people in each sample performing a number of actions, from 0 (no action) to 5 (all possible ones)

The frequencies of the performed actions are comparable in most cases. It should be noted though that the VR sample spent on average 3.55 min in the room from the time they noticed the smoke plum until the experiment was terminated, while the real sample spent between 0.5-4.5 hours in the room, depending on the time that it took to get rescued. Compared to the 34% of VR participants declaring having fire safety training, only 17% of the real sample claimed the same.

Fisher’s exact tests (using significance level= 0.05, which becomes 0.01 applying the Bonferroni’s correction) shows statistical differences between two of the actions (block vent *p= <0.001* and turn on TV *p= <0.001*), clearly no statistical differences for signalling outside (*p=0.690*) and no differences for opening the windows (*p=0.044*) and trying to use phone (*p=0.031*), as presented in Table 3.

Table 3. *Input and results for Fisher's exact test performed comparing both samples.*

	block vent		**open window**		**try to use phone**		**turn on TV**		**signal outside**	
sample	*yes*	*no*	*yes*	*no*	*yes*	*no*	*yes*	*no*	*yes*	*no*
VR	25	30	44	11	43	12	17	38	10	45
real	107	11	108	10	107	11	91	27	25	93
p-value	< 0.001		0.044		0.031		< 0.001		0.690	

3.6.2. Experiment 1: Questionnaire results (VR experience)

Participants were asked after the experiments to fill out a questionnaire to rate their VR experience. This included a set of questions concerning the reported feelings of insecurity, stress and fear (see Figure 10) rated from 1 (lower) to 7 (higher). Even though some of the participants reported high levels, no participant requested to terminate the experiment or made any comments concerning any hesitation about staying longer time in the virtual environment.

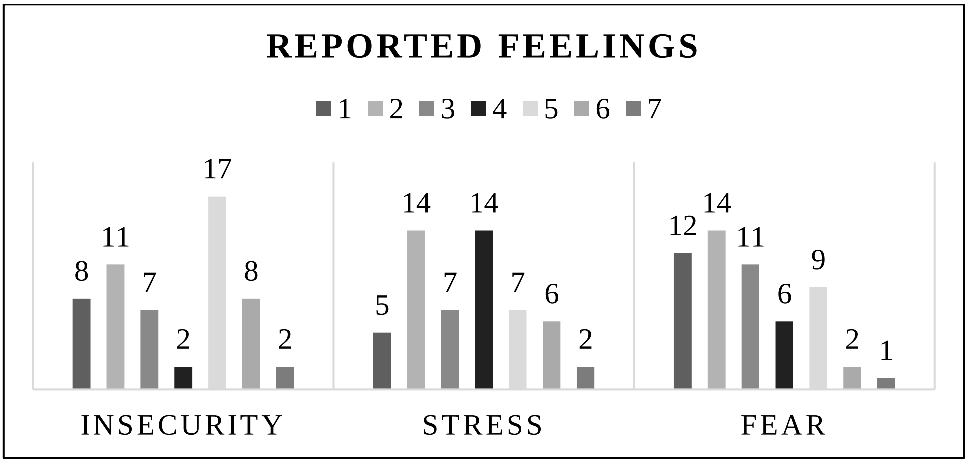

Figure 10. Rating of feelings experienced during the experiment. The rating corresponds to feelings related to the emergency situation, not the fact of being in an experiment.

Realism

The participants were asked to rate the realism of specific aspects of the VR experience (see Figure 11). This includes the visual aspect of the room, functionality and the smoke. The general outlook of the room was rated relatively high by most participants, with an average of 5.6. The functionality of the objects and the available interactions (i.e. how interactions work compared to real objects), was given an average score of 4.5. The smoke realism was rated with an average of 4.6.

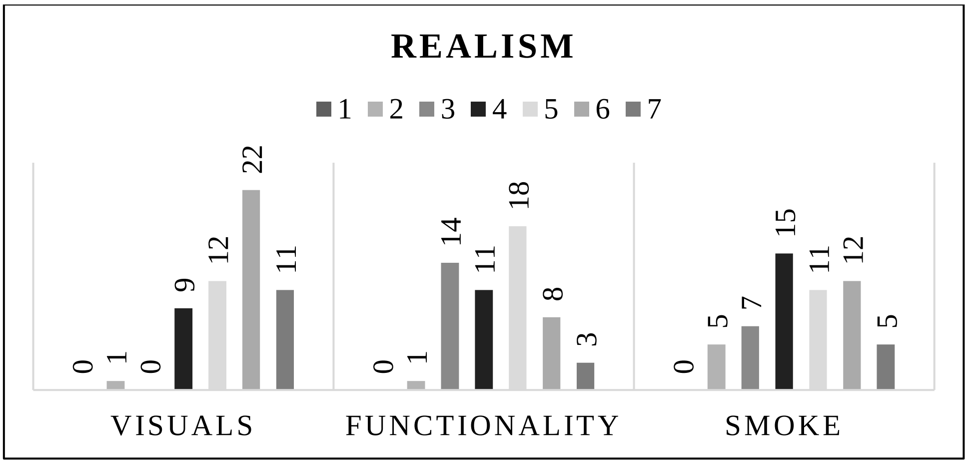

Figure 11. Rating of realism of different components of the VE, from 1 (low) to 7 (high). Visuals corresponds to the outlook of the VE. Functionality corresponds to the behaviour of the objects in the VE. Smoke corresponds to the outlook and the behaviour of the smoke.

Immersion

Participants were asked to rate their feeling of being immersed in the VR scenario (see Figure 12). Participants were given an example as "did you 'forget' that you were in a lab instead of a hotel room?". They had the option to select yes or no or to provide their own answer. Their own answer typically indicated that the immersion was intermittent throughout the experience, or feeling immersed but still aware of the virtual nature of the experience.

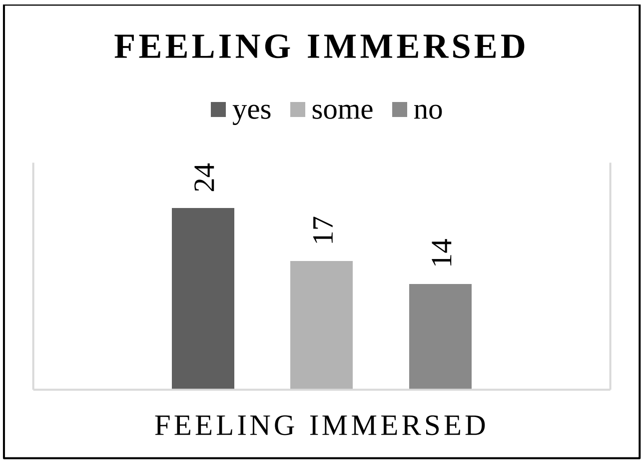

Figure 12. Answer to the question "Did you feel immersed?". Participants in the "some" category gave their own description of the immersion level, rather than choosing between the yes and no options.

Equipment

Participants were asked to rate the use of the hand controllers and the navigation around the environment, being 1 easy and 7 hard. Their answers are summarized in Figure 13. The use of hand controllers gave an average of 2.5, and walking gave an average of 2.3.

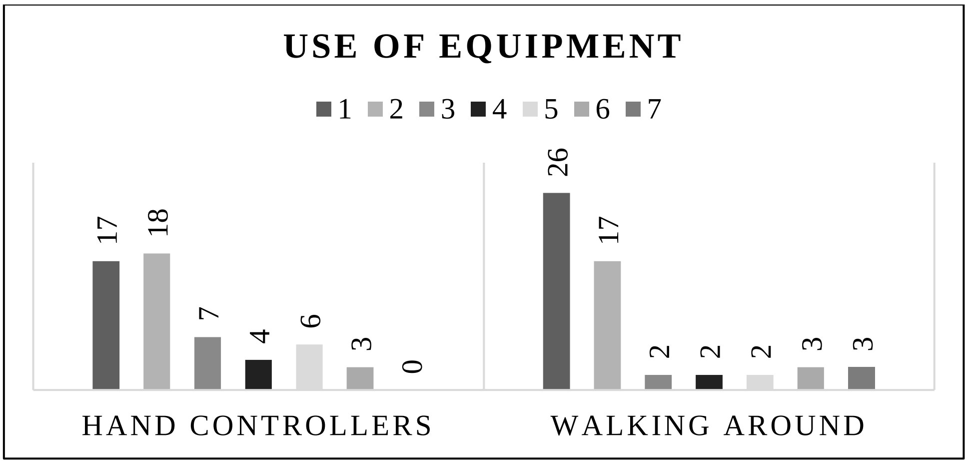

Figure 13. Rating of how easy it was for participants to use the equipment and navigate the environment, from 1 (easy) to 7 (hard).

Participants were also asked to rank their level of discomfort (see Figure 14). The vast majority gave a low rating for dizziness (average of 1.3 with a standard deviation of 0.7), and overall low level of discomfort in the eyes (average of 1.5 with a standard deviation of 1.2). The overall easiness to use the equipment and the low levels of discomfort indicate that the VR equipment did not interfere much with the participants' performance.

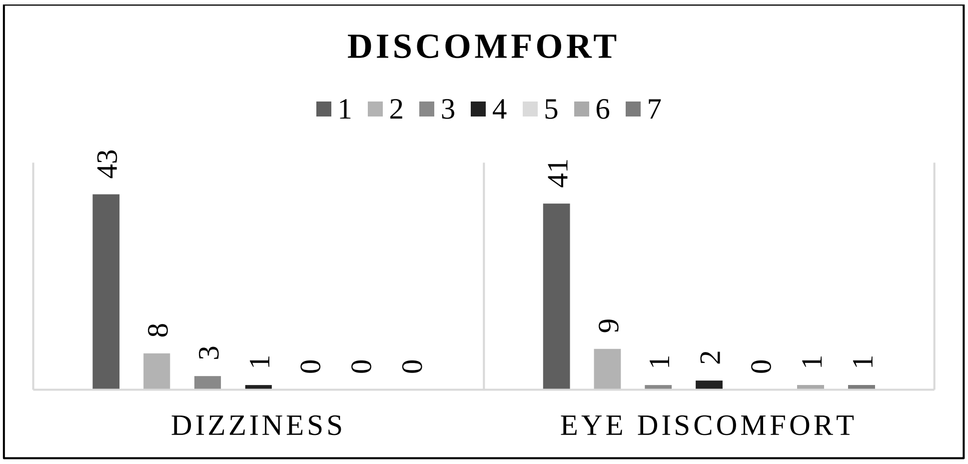

Figure 14. Rating of discomfort experienced because of the VR equipment, from 1 (low) to 7 (high)

3.6.3. Experiment 1: Qualitative observations in VR

The interviews with the participants and the observations during the experiments gave insights into the participants' experience. An important qualitative finding relates to the fact that some participants took the smoke (and the scenario in general) more seriously than others. It was evident that in some cases participants would move faster and a somewhat agitated breathing could be heard in the experimental room. This is in line with what could be expected during an actual evacuation.

Some participants who did not manage to block the smoke tried to deal with the situation in other ways. One participant attempted to lock himself in the bathroom, turned the shower on and used towels to block the gap between the bottom of the bathroom door and the floor. The same participant then laid down on the shower floor, under the stream, and waited. The experiment was interrupted as it was assumed that the participant would not leave the bathroom anymore. While interviewing him after the experiments, he reported that he would have stayed there "indefinitely".

A handful of participants who were immersed in the smoke also reported in different ways that they thought they were dead (assuming this was a real situation), see the three quotes below from three different participants:

"*I guess I'm dead*"

Participant number 42

"*I think I will die*"

Participant number 54

Participants who decided to remain by the opened windows reported in different ways their will to be rescued, see the two quotes below:

"*Now to wait*"

Participant number 27

"*I will wait to be rescued*"

Participant number 57

A portion of the participants (21%) decide to not open the windows to clear the smoke or opened them briefly and then closed them again. Once asked to why they performed such action, they mentioned issues associated with closing door and oxygen from their fire education in school. Once they were asked to explain in more detail their thinking process, it became clear that they referred to the fact that closing down the room may prevent the fire of getting more oxygen. The VR scenario helped to identify this misconception.

The differences between the VR and real samples were less in the use of the phone and their attempts to signal to the rescue services outside. It is a common concept to call the firefighters if there is a fire, so it is not surprising that most people tried to do so. When looking into the signalling outside percentages two different sources of bias come into play. First, the VR sample heard sirens and a helicopter, but they could not see them. They could not see fire trucks on the streets or any sort of rescue services they could try to get the attention from. This means that the VR sample may have had little incentive to try to signal their presence in the room. On the other hand, the data provided by the real sample may not be fully reliable. Only 20% said they did so. However, most of them stood by the windows to breathe. The fire occurred during daytime, so the occupants standing at the windows were fully visible for the rescue services, which were also giving them instructions on their bullhorns. Therefore, it is likely that the victims did not need to actively indicate their presence in the rooms. While there is only a small difference in the behaviours of the two samples, their conditions were not quite comparable and the small difference seems to be a coincidence.

Closing doors and windows when a fire is detected might be a useful action to do in certain fire scenarios, but it was hardly a good idea in this one. First and foremost the idea in that concept is not to lock oneself up with the fire but to close the room down on their way out in order to try to reduce the amount of available oxygen for the fire and even more importantly prevent the smoke to spread into the rest of the building. Secondly, but maybe harder to realize from the participant's perspective, the fire was nowhere to be seen. The participants at some point all knew the ventilation system was spilling smoke into the room and the hallway was filled with smoke. There were no visible flames or any indication of where the fire was. This matches what many victims of the real fire stated in their questionnaires: they did not know where the fire was and some of them were checking the hallway in case the flames were approaching. What the participants' behaviour in this case shows is a misconception they made from the fire safety training they may have had.

Only a third of the participants claimed they have received fire safety training before, most of them getting it at school or in the workplace. It seems likely that the misconception is due to the participants remembering loose parts of the training and "connecting the dots". In a real case, the smoke affecting breathing and the visibly clear air outside the window would most likely convince them to open it. This was not the case for many victims in the MGM Grand fire, many of which had the conditions of the room worsen after they broke open the windows, due to smoke coming in from the outside. While the identification of a misconception some participants made out of their fire training was a serendipitous result of this experiment, it highlights the power of VR as a tool for training purposes. The trainees can learn the theory by different means, and that learning can later be tested in VR, by subjecting them to challenging scenarios that combine different conditions in a complex event.

When comparing the VR sample to the real sample, slightly less than half of the VR sample blocked the smoke coming in through the vent, compared to most of them in the real sample. In the VR scenario, participants could choose not to do anything about the smoke and have no serious consequences. In the real fire, smoke in the room affected the breathing of the victims, forcing them to find fresh air or limit the amount of smoke entering the room. Other participants mentioned that they did not know how to react, even mentioning they panicked, so they did not do anything. For an external observer, there was no panic, or at most that panic can only be described as lack of actions (Fahy et al., 2012).

Another qualitative finding relate to the fact that participants mentioned in the questionnaire the lack of a fire alarm going off, the lack of instructions on what do to in a fire and the lack of a floorplan in the hotel room. They reported those variables as affecting the realism of the VR scene. These elements were not included in the VR scenario as the MGM hotel was not equipped with these at the time of the fire.

Experiment 2: Social influence

The analysis of experiment 2 focused on the assessment of when the decision to evacuate was made. The key moments that triggered the evacuation for each participant was recorded, the effect of single and multi-player conditions was analysed, as well as the exit choices they made and their behaviour during the evacuation.

3.6.4. Experiment 2: Decision to evacuate

Figure 15 presents the proportions of participants leaving at each key moment. The distribution of participants leaving at the different key moments is roughly the same (ca. 24%), with slightly less participants leaving after watching the extinguishing attempts. A small group (7.5%) did not attempt to leave the nightclub.

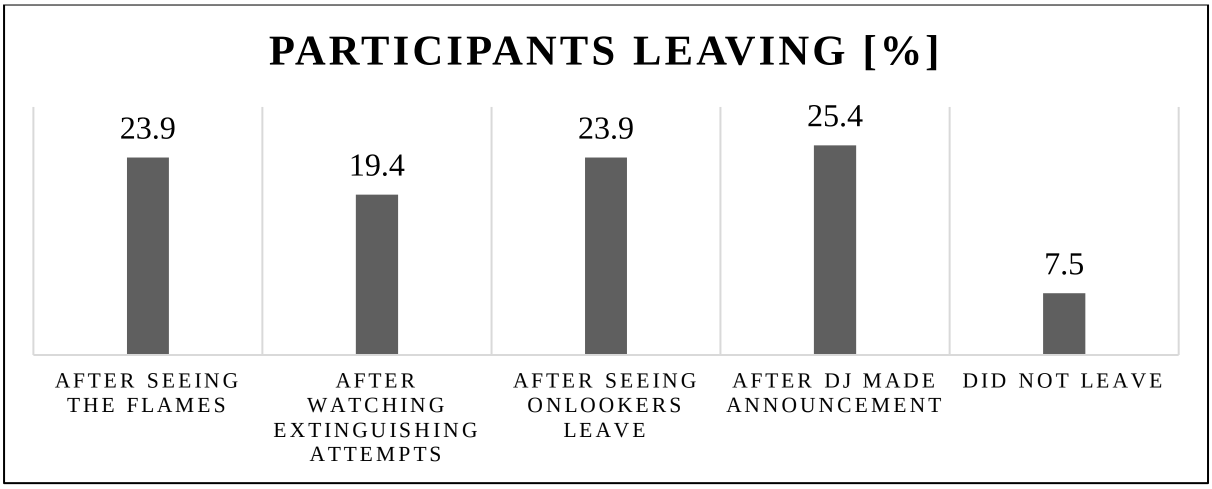

Figure 15. Proportion of participants leaving after different key moments. It should be noticed that these key moments were sequential (here left to right), and the effect of each should be considered in composite with the previous ones.

Analogously, Figure 16 shows the same analysis, this time made for both samples (single and multi-player).

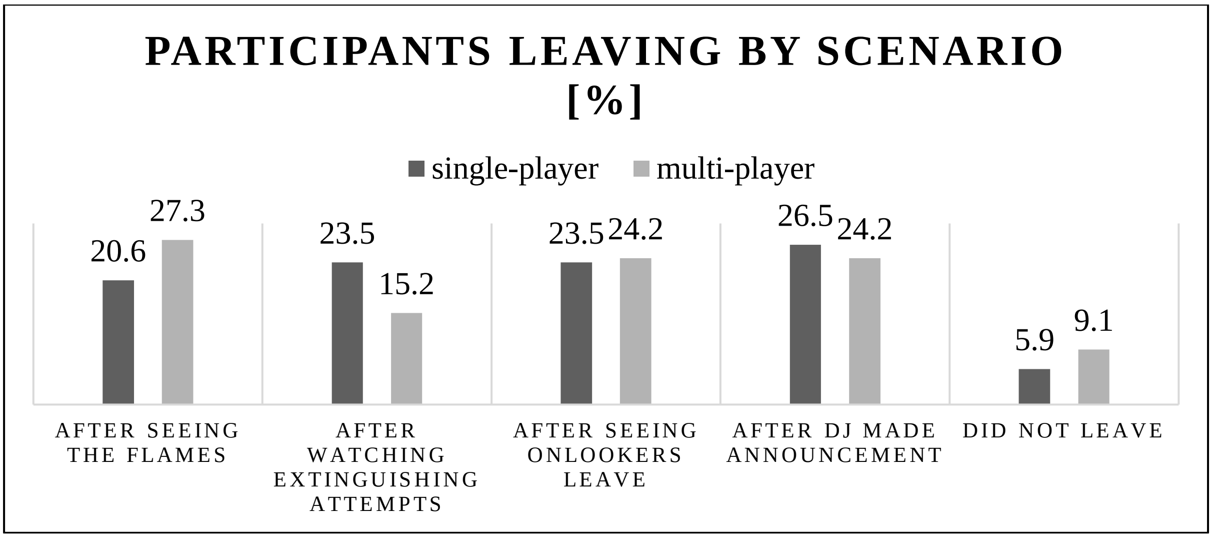

Figure 16. Proportion of participants leaving after different key moments, split by single-player and multi-player.

The participants in the multi-player sample were asked if the "presence" of the player in the remote laboratory affected their behaviour. Most of them answered they forgot about that other player after a while. Only two stated they looked for the other player especially after they realized there was a fire. From those two, only one did not leave the premises at all. This participant, participant 54, mentioned he or she put much effort into finding the other player after the fire occurred.

Statistical testing (a Fisher's exact test with assumed significance level equal to 0.05) was made and no significant differences were found between the single-player and the multi-player results concerning the number of participants performing each action (see Table 4).

Table 4. Results of statistical testing (Fisher's test) concerning single player and multi-player results.

	after seeing the flames		after watching extinguishing attempts		after seeing onlookers leave		after DJ made announcement		did not leave	
	yes	*no*	*yes*	*no*	*yes*	*no*	*yes*	*no*	*yes*	*no*
single-player	7	27	8	26	8	26	9	25	2	32
multi-player	9	24	5	28	8	25	8	25	3	30
p-value	0.576		0.539		1		1		0.673	

The exit each participant used was recorded, and the proportions of participants using each exit is presented in Figure 17. The data does not show a preference from the participants for that exit. Exit C was the most used, with 38.8% of participants going for it. It was the closest one to the location of the fire and therefore the closest to the location of the participant.

Figure 17. Proportion of participants using the different exits. Exit C was the closest to the fire.

Additionally, apparent attempts by the participants to alert other patrons and signs of hesitation on their decision to evacuate were recorded. The attempt to alert others was identified as the participants waving their hands in front of the avatars or trying physical contact to get their attention. Avatars were completely unresponsive to any attempt of interaction. The hesitation was identified as the participant repeatedly looking back while walking towards one of the exits. Hesitating participants stopped walking and looked back either at the fire or at the occupants (it was not possible to determine precisely what they were looking at in the scene). Figure 18 shows the proportions of participants doing each action.

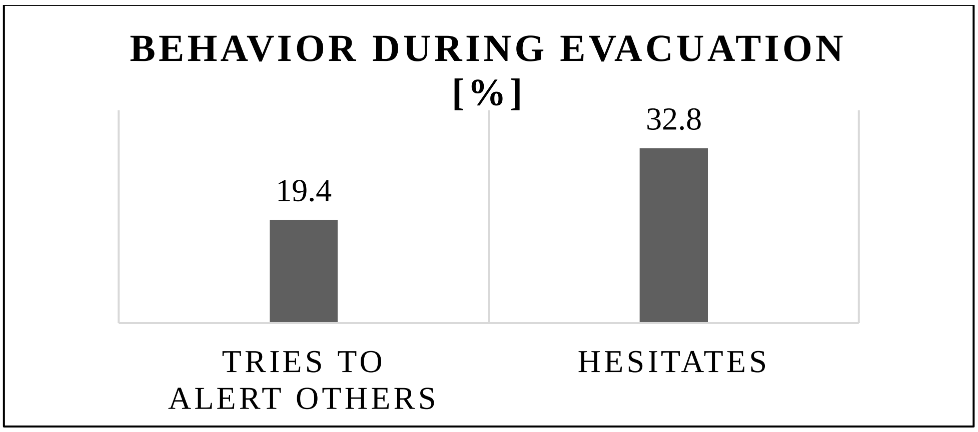

Figure 18. Proportion of participants attempting to alert others and hesitating.

3.6.5. Experiment 2: Questionnaire results (VR experience)

The assessment of the VR experience on itself is necessary to obtain information on the ecological validity of the VR experiment. Participants were asked to fill out a questionnaire and rate the feelings they experienced during the experiment to assess their mind-set due to the emergency they were exposed to. The rating went from 1 (lower) to 7 (higher). Even though some participants reported medium or relatively high levels of insecurity, stress or fear, no participant requested to terminate the experiment or made any comments concerning any hesitation about staying in the virtual environment any longer. Figure 19 shows the number of participants rating each feeling.

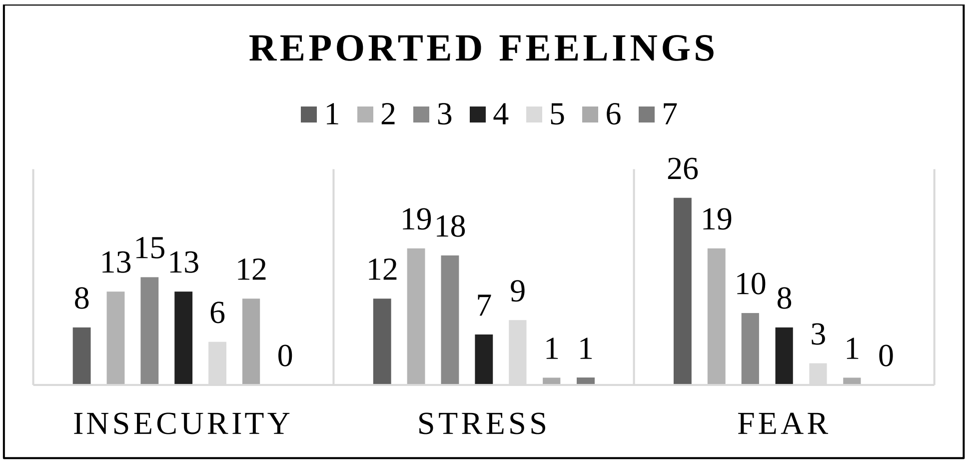

Figure 19. Number of people giving a certain rating of feelings they experienced during the experiment, from 1 (low) to 7 (high). The rating corresponds to feelings related to the emergency situation, not the fact of being in an experiment

Realism

The participants were asked to rate the realism of specific aspects of the VR experience (see Figure 20). This includes the visual aspect of the nightclub, the people in the club, the fire and smoke, and the extinguishing attempts. The general outlook of the nightclub was rated above average, with a score of 4.9. The people in the club got a 3.5 score in average. From the participants' comments in the questionnaire, it became clear that the lack of reactions from the avatars and the empty expressions on their faces felt unrealistic. The fire and the smoke got an average score of 3.7, also being brought up as not very realistic in the comments. Lastly, the extinguishing attempts got a score 3.4. It should be noticed that about a third of the participants (21) claimed not to have seen them.

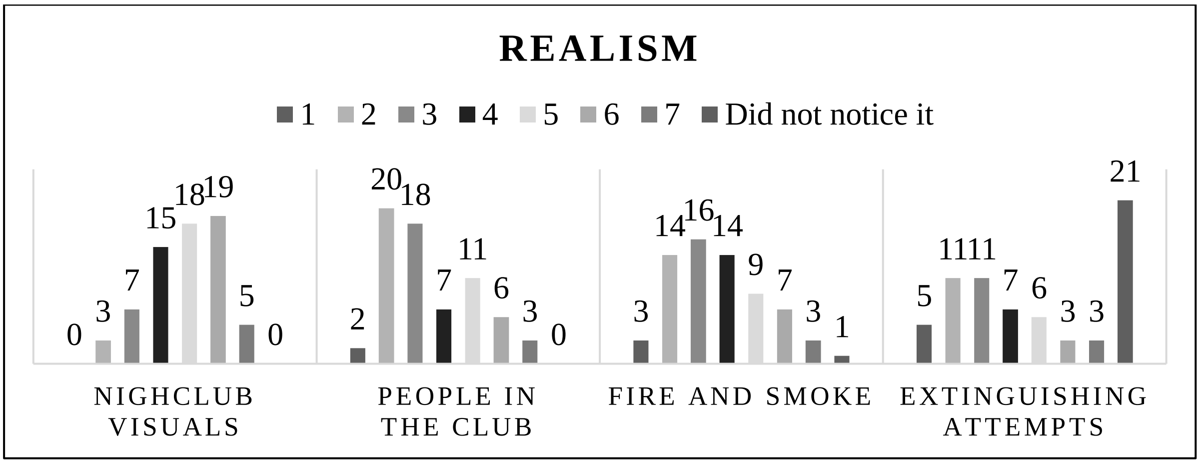

Figure 20. Number of people giving a certain rating of realism of different components of the VE, from 1 (low) to 7 (high). Nightclub visuals corresponds to the outlook of the VE. People in the club corresponds to the avatars in the VE. Fire and smoke corresponds to the outlook and the behaviour of both the fire and the smoke. Extinguishing attempts corresponds to the outlook and the actions performed by two avatars using extinguishers.

Immersion
Participants were asked to rate their feeling of being immersed in the VR scenario. Participants were given an example as "did you 'forget' that you were in a laboratory instead of a nightclub?". They could rate their immersion level from 1 to 10 (low to high), and could comment on their response. The average score given by the participants was 5. Many participants mentioned the "intermittent" nature of the immersion, or a "half immersion", which was explained as feeling immersed sometimes and sometimes not, or feeling they were in both places (the VR laboratory and the nightclub) at the same time. Figure 21 presents the immersion ratings. Results seem to indicate a quite large variation in the perceived level of immersion among the participants.

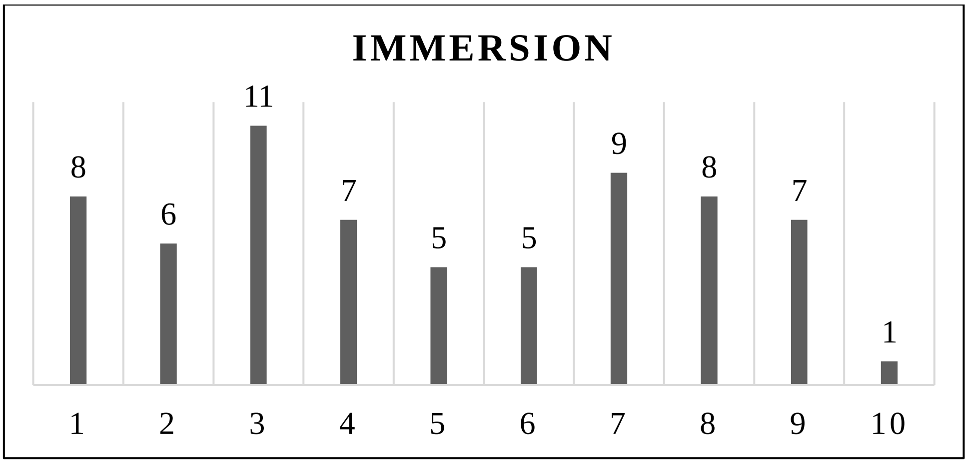

Figure 21. Number of people giving a certain score to the question "How immersed were you in the VR world? (did you "forget" that you were in a laboratory instead of a nightclub?)", from 1 (easy) to 10 (hard).

Equipment
Participants were asked to rate the use of the hand controllers and the navigation around the environment, being 1 easy and 7 hard. Their answers are summarized in Figure 22. The use of hand controllers gave an average of 3.3, and navigation gave an average of 3.6.

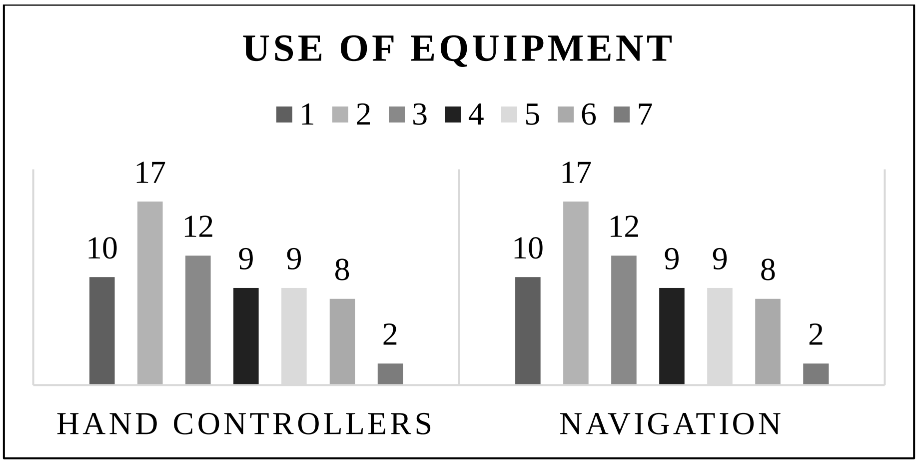

Figure 22. Number of people giving a certain rating of how easy it was for them to use the equipment and navigate the environment, from 1 (easy) to 7 (hard).

Participants were also asked to rank their level of discomfort (see Figure 23). The vast majority gave a low rating for dizziness (average of 2.6 with a standard deviation of 1.6), and overall low level of discomfort in the eyes (average of 1.9 with a standard deviation of 1.2). The overall easiness to use the equipment and the low levels of discomfort indicate that the VR equipment did not interfere much with the participants' performance.

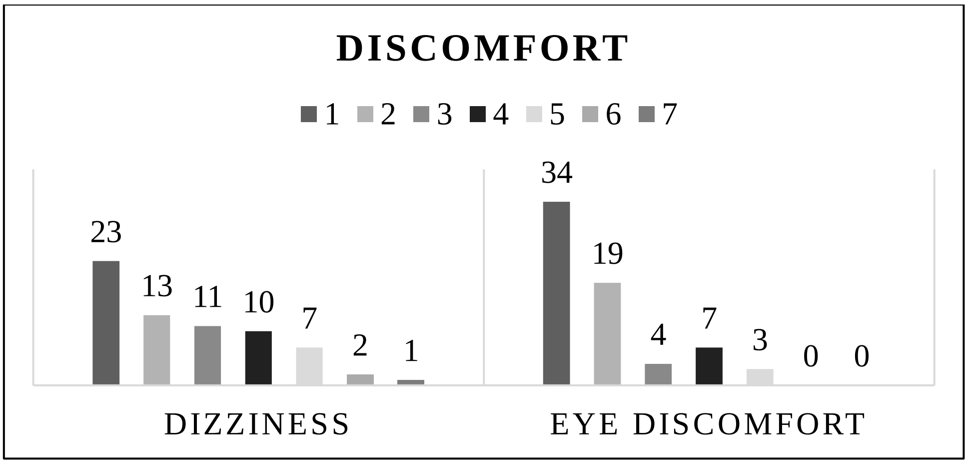

Figure 23. Rating of discomfort experienced because of the VR equipment, from 1 (low) to 7 (high).

3.6.6. Experiment 2: Qualitative observations in VR

The answers to the questionnaire as well as the observations during the experiments gave insights into the participants' experience. The participants' comments highlighted again the discrepancies between what is expected as fire safety features in a modern building compared to what was available at the time the fire took place. Many participants mentioned that it was unrealistic that there was no fire alarm going off, that the music did not stop when the fire was detected, and that the people did not immediately leave the premises. As mentioned before, while their comments seem reasonable, during the real fire the situation was the same they experienced in VR, as in the Report of the Tribunal (Keane, 1982), some people even kept dancing once the fire started to cause a commotion and extinguishing attempts were made.

Panic was constantly brought up in the comments. Participants rated the lack of panic in the room as unrealistic, although existing research define this as a misconception (Fahy et al., 2012). A few mentioned they panicked themselves, although it was unclear how their panic was any different from the non-panicking reaction from other participants.

4. Discussion

The VR experiments performed to investigate the potential of the ForensicVR methodology provided useful insights into its benefits and limitations.

The ForensicVR method benefits are associated with the low risks of the VR experiments compared to corresponding physical experiments, which would likely not be possible to conduct due to ethical reasons. The ForensicVR methodology seems to offer the possibility to create a reasonably accurate virtual replication of the fire scene, and obtain an additional perspective to the forensic investigators. This is linked to the fact that investigators can follow the actions of the participants in the virtual environment on a computer screen, and see what the participants see and do. This could give insights into how fire victims understood the information that was available to them, what actions they performed, in which sequence, and what consequences those had on their survival. In addition, the ForensicVR method could also provide information about what-if scenarios, i.e., the effectiveness of systems that were not in the building and in general what features of the building may affect the outcome of the fire from an evacuation perspective.

VR should not necessarily be considered a replacement for other research techniques. As a matter of fact, VR seems to compare well to classical laboratory experiments (Kinateder et al., 2014). The VR experiments performed here for the validation of the methodology showed that although complex actions can be reproduced in VR, different people may take the VR scenarios more or less seriously, thus affecting the validity of the results obtained. For instance, in the individual behaviour experiment, more than one of the participants did not block the smoke coming from the vent. These participants saw the smoke clearly, and in some instances, they even tried to disperse it by waiving their hands on the plume or using another object as a fan. In fact, some participants continued to test the physics of the VR scenario. In fact, one of the participants wrote in the questionnaire that they "Wanted to experience as much as possible from the VR session, and then the fire started and severely limited my time in there!". This kind of behaviour could be due to the novelty of VR. Many participants mentioned they signed up out of curiosity, and that they have never tried it or only very briefly. From that perspective and knowing that the experiment description invited them to try a realistic VR hotel room, it can be argued that the smoke was more of an inconvenience for them than a part of the experience.

Many participants showed some sense of urgency with respect to the fire and smoke. In experiment 1, it was observed that in most cases, that that sense of urgency would diminish or disappear once the participants managed the smoke effectively and the smoke layer was leaving the room.

The lack of urgency or the lack of consequences to inaction in VR could be avoided by adding features to the VR experience that could give the participant an idea of deteriorating health. These features can be analogous to the "health bar" in videogames, which is widely used as an indicator of the physical condition of the player. In the context of human behaviour in fire, indicators of temperature and breathability could be used. These features are yet to be developed and its effect tested in future research.

A large difference in percentages between the two samples in experiment 1 was also observed in their attempts to turn on the TV to look for information about the fire. This could be linked to anachronism of this solution nowadays where smartphones provide real time information, but this could also be linked to the clear difference in the total time the two samples spent in the hotel room. The real sample did not only have more time to look for other actions they could do, they also were in a life-threatening situation and they needed to increase their odds of survival by any possible mean. These two factors were not present in the VR scenario, which could have led to the VR sample trying less alternatives.

Future research should focus on exploring the effect of a longer experiences in virtual environments. This issue should be considered in light of possible impatience of participants, as some showed signs of impatience after a couple of minutes, when they did not know what else to do. Prolonging their time in the VE could lead to them to request to stop the experiment out of boredom. A follow-up experiment investigating the link between patience levels in virtual environments and subsequent actions could show how this variable affects behaviours.

Another advantage of using VR for studying human behaviour in fires is VR's relatively low cost compared to a classic laboratory experiment or a full forensic reconstruction of a fire scene. Given the current state of the art allowing the development of virtual environments with a high degree of realism and the possibility to easily manipulate hazardous conditions, VR is highly suitable for research on human behaviour in fire (Kinateder et al., 2014b). In fact, a VR reconstruction enables replication of a fatal fire evacuation scenario without exposing people to life-threatening hazards. At the same time, VR represents a methodology involving minor risks in terms of safety for the test participants. High experimental control can be achieved in VR experiments as well as different setups of the same scenario can be tested in a relatively inexpensive manner in comparison to other methods. VR allows in a cost-effective way to modify the studied environment, thus permitting the investigation of several behavioural variables of interest.

The level of realism reported by the participants could be due to the fact that certain objects had limited functionality in VR. These functionalities could be improved in the future, thus further enhancing the ForensicVR validity. From the participants' comments after the experiments, insecurity was reported in some instances because they did not know how they should behave. While the stress level varied among them, it is remarkable that the experience stressed them to some extent, considering that the threats they were experiencing in VR were not real and they were very well aware of this issue. The reported panic behaviour was indeed often brought up by the participants. This issue is largely in line with reports from actual events in which the mis-conception of panic to describe other people actions but not their own often occurs (Fahy et al., 2012).

This outcome and the fact that the participants performed the actions without being instructed to do so show the potential of the ForensicVR method. The scenarios were credible enough to prompt them to try to tackle the problem as they would do in reality in a similar scenario, even though they signed up only to test a VR scenario. Several participants reported that at some point in the experiment, they forgot about their real surroundings, but that was not constant throughout the experiment.

In the case of experiment 2, the level of realism was affected by both the lack of reactions from the avatars to actions by the participants, and the lack of emotions on their faces. Participants mentioned that the avatars did not look very realistic, even cartoonish. Including more animations in the VR scenario could solve the problem of lack of reactions, although it is expected that participants would keep testing the avatar until its reactions become repetitive or unrealistic. Sorting out the issues of the uncanny valley may be one of the biggest challenges of using VR in group settings (Mori, 1970; Seyama and Nagayama, 2007).

The majority of the participants considered that the hand controllers were easy to use, which would increase their level of control in the interactions with the environment. It should be noted that this may be linked also to the young sample characteristics (mostly Swedish students), thus further studies should investigate this issue with a sample including older people which may have less experience with gaming.

Some participants pointed out the mismatch between their expectation of fire safety features in a building and what they encountered in the VR scenarios. This points into possible implications of anachronism in a VR scenario. The mostly Swedish sample of people taking part in this experiment is used to certain standards of fire safety systems, like fire alarms and sprinklers that were not necessarily in place in the reconstructed scenarios. The participants' behaviour is intrinsic to the current times, and therefore they expect the current standards to be in place. This could also explain why there were less participants turning on the TV looking for information about the fire in experiment 1 compared to the victims of the real fire. Therefore, the ForensicVR method is likely to have a higher ecological validity in a scenario representing a modern emergency scenario.

5. Conclusion

The experiments support the use of VR to study human behaviour in fire and they demonstrated that they have the potential to be greatly useful to reproduce and interpret human behaviour during fires. In addition, they can help identifying misinterpretations of fire safety education, and they represent a cost-effective way to investigate what-if scenarios during forensic investigations.

The ForensicVR project has shown that participants in a VR experiment can be expected to attempt and succeed at performing both simple and complex actions when exposed to a fire evacuation scenario, even without being instructed to do so. They would also attempt to evacuate even if the majority of other occupants in the premises do not do so.

Participants in the VR scenarios behave in a comparable way as the victims of the real fire, performing the same actions as the victims do, which hints on the potential of the ForensicVR method. Nevertheless, while the actions are similar, the behaviour observed rely on the type of participants taking part in the experiments, i.e. some participants are keen to explore VR scenarios than performing as in the real world. In order to successfully use the ForensicVR method and improve its applicability to several types of participants, it is advisable to improve the sense of urgency by adding VR features which enhances it.

The two sets of experiments therefore conducted allowed to achieve the main aim of the project, i.e., developing and testing the potential of the ForensicVR method.

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