Virtual reality as a communication tool for fire safety – Experiences from the VirPa project

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Abstract. This paper presents a serious game on fire safety that utilises virtual reality (VR) technology. The game represents an office being engulfed in smoke while the player's task is to escape the building, but the player is not aware of this goal before the fire alarm is triggered in the game environment. This radical shift in game dynamics is an authentic representation of the unexpected nature of an actual fire alarm. The game was mainly designed to collect information on players' actions for analysing them as representations of human behaviour in a real fire situation. For our study, 169 people played the game in controlled environments. The recorded metrics demonstrate the potential of VR applications as tools for fire-related learning and behavioural analysis, while the results from a post-game user experience questionnaire show that the players were highly engaged in the fire evacuation task and found the VR application to be an appealing training environment. This paper analyses the pros and cons of the game design project and proposes actions to be implemented in future VR games on fire safety.

Keywords: Virtual reality; Serious games; Fire safety; User experience

1 Introduction

Fire safety education has two aims: 1) to change peoples' behaviour so that fire mortality and morbidity rates decrease and 2) to provide information that helps people to understand the risks involved and respond to emergencies. In practice, fire safety refers to either preventive measures in the case of fire or to limiting the spread of fire and smoke [1]. As fire safety situations are difficult to practice in real life environments [2], virtual reality (VR) applications become a fruitful context for educational aspects relating to fire safety. Fire-related injuries are expensive to treat and the healing process is long. In Finland, the number of fire-related deaths is relatively high compared with the other Nordic countries [3]. Previous fire safety research shows that people tend to ignore fire alarms, dismiss exit signs, and lack awareness of escape routes [1, 4, 5]. These facts, combined with figures of fire deaths caused by people who could not exit in emergency situations, have raised needs for innovative methods for fire safety training.

This paper introduces the VirPa project where VR technology was applied to the theme of fire safety. The project aimed to determine whether an immersive and realistic

VR game is a suitable tool for interactive fire safety learning and communication. By "learning", we refer not only to individuals' knowledge, skills, attitudes and values, but also to their ability and will to act in specific situations [6]. Furthermore, "communication" is viewed not only pedagogically, but also the other way around as a possibility for obtaining information about human behaviour and the type of decision-making that occurs in a VR environment. The paper presents empirically collected data related to the behaviour and user experience (UX) of the players in an unexpected fire situation, which is discussed from the points of view of fire safety and game design.

Overall, 169 test subjects participated in the empirical study covering four different target groups: 14-year-old children, university students, office workers and fire departments employees. The game recorded player actions during the fire situation based on predefined criteria, whereas their experiences were surveyed with two UX questionnaires immediately after the game was finished.

Our hypothesis is that relating to fire safety, a VR game such as VirPa is able to function as a communicational tool with a strong pedagogical potential. The overall analysis touches upon the performance of the subjects in the escape task and on the efficiency of the game itself to collect data. The discussion also concentrates on how possible training needs regarding fire safety as well as possible benefits and gaps in the game design can be brought forward via data analysis. From the design-driven point of view, collecting player experiences helps to evaluate the effectiveness of the VR in the fire safety context, thus contributing to the future design of systems. To that end, the paper aims at identifying game-related issues that are worth taking into account when designing the narrative continuum for a serious game similar to what we present here.

2 Fire Safety in Virtual Reality

Serious games are games developed for more than pure entertainment. A serious educational game can be fun, but it also needs to teach something new to the players or strengthen their existing knowledge. Serious games in VR are used for educational purposes [7], specifically to enable learning while performing simulated activities, which are dangerous and even impossible to be performed in the real life [8, 9]. Technical details for improving effectiveness, entertainment value and player engagement have been discussed for instance by Arnab et al [10].

Within the domain of fire safety, VR has been applied in many ways. For instance, in training general public in evacuation and rescue situations in road tunnels [11, 12] and in university buildings [13]; in improving fire safety skills of children and their evacuation behaviour in residential buildings [14, 15]; in training firefighters in general [16] as well as for optimal rescue path selection [17]; in estimating the behaviour of people in danger [18]; and to understand human behaviour in fire [9]. The game-based firefighter training simulator called Sidh was used in a feasibility study to analyse the performance and reflections of 31 firefighter students [16]. The study proved Sidh to be a useful complement to traditional firefighter training methods partly thanks to the high entertainment value achieved by the game. The entertainment value was considered an important issue for game engagement and volunteering for additional training.

In a study by Chittaro & Ranon [13], the players knew the game scenario and the procedures to follow in case of fire in advance and received pre-assigned goals to fulfil during the game. The players indicated that the game lacked emotional intensity for creating stress and anxiety. Only a few studies have considered children as test subjects [19]. Children have found virtual experiences fun and intriguing in fire safety skills training [15] and on the other hand, fire safety skills of primary school students have significantly improved with the use of virtual reality based training [14]. In the study in question, an expert was in-situ to offer training designed to enhance the behavioural skills of the children (N=10). The study interestingly reported some kids purposefully walking close to the fire to examine the boundaries of the game, which is an illustrative example of how any data-based behavioural analysis should take into the account the game-like quality of any VR application. A literature review by Feng at al. [19] revealed evacuation research studies conducted as serious VR games, which succeeded on their pedagogical and behavioural objectives. Regarding those, our study reaches outcomes in behaviour recognition and hazard awareness, which were hard to find from fire evacuations studies evaluated in the review. Moreover, many of those studies applied protocols to reveal the domain of study to the user, thus potentially decreasing the possibility of recording authentic player responses and experiences. In our study VirPa, the study protocol conceals the pedagogical objective, the shift in the goal of the game only emerging during game play. As a result, the research setting and the player experience in the VirPa game are both quite unique.

3 Game Concept and Implementation

3.1 Virtual Environment

The created virtual environment was a three-floor office building divided into three wings, A, B and C. Different views of the building are presented in Figures 1–3. The height of the rooms was 3.6 meters. Non-playable characters and typical office furniture were placed around the space1. Sounds within the space included footsteps, copying machines, elevators, toilet flushes, ventilation noise, office music and the fire alarm itself.

3.2 Game Play and the Narrative

The goal of our game was to escape from the building once the fire alarm was triggered, but the player was not told about the true objective goal in advance. This decision aimed to simulate the unexpected event of a fire in real life. The communication with the test subjects followed a highly controlled protocol. The test subjects were invited to participate in a research project where actions and performance would be recorded for further analysis and during which they should behave as similarly as possible to a corresponding real life situation. The narrative was presented to the players as a job interview in a

[1] The making of VirPa video can be viewed here: https://youtu.be/ZWnM_9blB5M.

building – everything else relating to the game was left to players to discover themselves during gameplay.

The game begins in the main lobby of an office building (Fig. 1-a), where Ines, a non-playable character, provides the player with instructions like: "*My name is Ines, and I will guide you through the building until the third floor, where you will participate in a series of tests*". Teleporting method typical for VR movement (Fig. 1-b) was used to move between points, following Ines to the third floor for the revelation of the game's hidden agenda. The path to the target destination was not the most direct one, which offered time for the players to familiarize themselves with the game environment and mechanics. In the target office room, Ines asked the player to perform the Hanoi Towers game (Fig. 1-c). This cognitive task was selected to catch the attention of the player before the fire alarm would be triggered. The alarm was set to sound once the player had done eight movements in the tower game or 20 seconds had passed since its beginning. The sound level and the quality of the fire alarm was adjusted so that it would not be extremely loud nor especially annoying. From this moment on, the software started to follow and record all player actions, metrics N1–N19 in this paper. This information was saved on an *.csv file for later analysis relating to the behaviour of each player. The game could end in one of three ways: escaping, dying or finding shelter. The third option was activated when taping the door shut from inside certain rooms. Once the game ended, the subject filled in both an in-game UX questionnaire and a paper-based questionnaire with open questions.

From a game design perspective, the game was meant to be played out quickly, if the player managed to make decisions that would have made sense in a real-world situation. The gameplay was designed to fuel player engagement throughout the experience. The most important factor in this was naturally the fire alarm itself, which shifted the goal of the game entirely from a mundane task into an extraordinary situation. Other such elements were for instance blocking the closest escape exit due to renovation work (Fig. 1-d), filling up a stairway and corridors with smoke (Figs. 2-a, 2-b) and creating a less than clear layout of the building itself (Fig. 2-c).

The plan for in-engine data extraction (discussed in the following main section of the paper) was directly linked to the game design and to the pedagogical approach that could be called a "flipped virtual classroom". In the approach, the content delivery of the substance matter – in this case relating to fire safety – takes the form of an unexpected turn in a gameplay context. In effect, the gameplay forces the players to put into practice their previously acquired knowledge regarding fire safety. The game did not offer direct instructions on how to react to the fire alarm. However, many visual cues were provided for the player in different ways. There were escape exit signs and floorplans on the walls (Figs. 2-d, 3-a). Smoke also clearly indicated where not to go (Fig 2-b). The player would never face any flames, death only occurring due to smoke inhalation. As later discussed, the game design forced the smoke flow faster than what the FDS simulation revealed to be the case in real life. This enabled the game to be played in just a few minutes. The software included a tracking system to verify whether the player centred their vision on the escape signs and the floorplans, which made it possible to analyse whether the player used that information to orientate and find an escape route. We also controlled the moment in which players encountered smoke for the first time. Depending on player actions, it would typically occur at three different situations: in the stairs between 1st and 2nd floor when players aims to escape by the main entrance (Fig 2-b), at any point of the corridors if enough time has passed while looking for an exit (Fig 2-c), and in the initial office room if the player was slow to react and leave the room. Figures 3-b, 3-c, 3-d present other situations occurring in the game: interaction with an NPC, phone interaction and a view of the fire department outside the building.

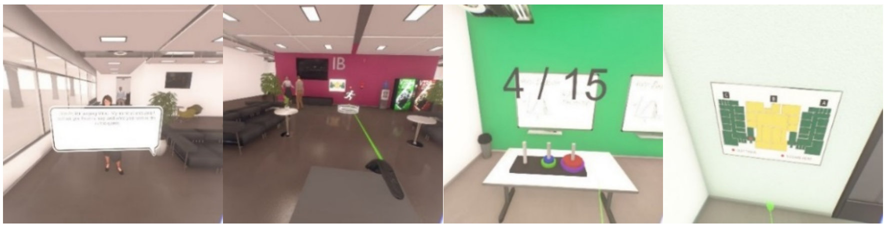

Fig. 1. a) NPC Ines explaining the initial gaming situation to the player, b) View of the lobby and the use of teleporting, c) Cognitive test Hanoi Towers to catch the attention of the player before fire alarm. d) The floorplan of the building as seen in the game.

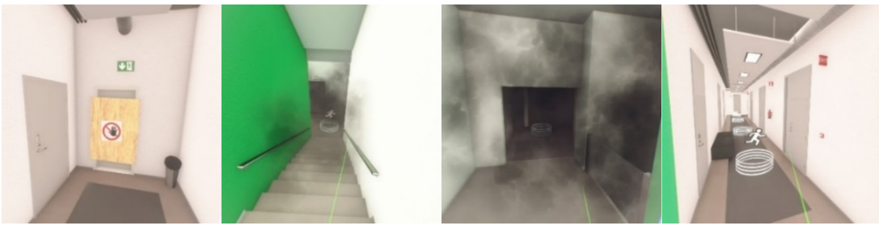

Fig. 2. a) Fire exit door not in use because of renovation, b) Smoke flowing through a staircase, c) Smoke impairing visibility, d) View of corridors with teleporting points.

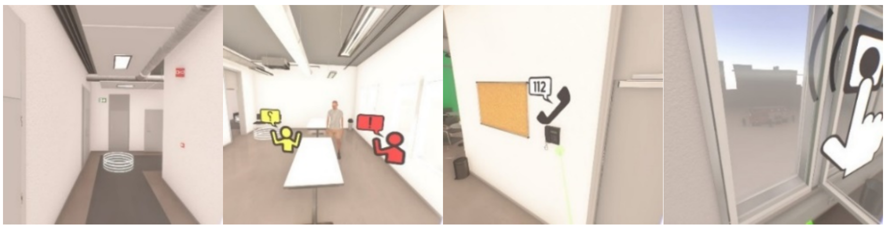

Fig. 3. a) Corridor with escape exit sign, b) Interaction with NPC when the fire alarm has been triggered, c) Possible interaction to call 112, d) Fire department outside the building as seen through an opened window.

3.3 Game Mechanics and User Interface

The game was created in Unity and it was played with HTC Vive gear including headphones. The game was played with only one controller, which acted as a laser pointer to indicate the location where to move next using the teleporting spots (Fig. 1-b). The trigger button, operated with the forefinger, was used to confirm teleporting and interaction to open doors and move the Hanoi Towers rings. Teleporting was chosen as the moving system in order to avoid any undesirable effects related to motion sickness [20]. Once the player selected the next point to move, a fade-out and fade-in effect was applied to the image in order to enable a less distressing transition from point to point. This system was a trade-off between the naturalness of the environment and the usability of the game for first-time players. Because there would be no further instructions available after the fire alarm triggered, the usability aspect was of utmost importance to ensure the fullest possible engagement from players after the goal of the game was shifted accordingly.

3.4 Smoke Flow Simulation

Smoke flow was considered a key element in the project to obtain physical realism. It was computed with FDS, a fluid dynamics simulator developed by National Institutes of Standards and Technology, NIST [21]. The simulator enables the calculation of the physical behaviour of smoke and other low speed flows. The results of the simulations were then converted into charts, which the game engine used to control the smoke in the VR application. The results were analysed with SmokeView [21], see Figure 4. The results of the simulations were presented to a group of specialists from South-West Finland fire department who confirmed their correctness. In the simulation, the fire started on the server room located on the 1st floor. The inflammable material was cable neoprene. This type of fire is quite exceptional, but it was chosen because of its high production of smoke and poisonous gases. The metrics gathered from FDS were visibility [m], temperature [C] and carbon monoxide concentration [ppm]. The flow was modelled with a high density grid, but data points for the metrics in FDS were set sparsely, for instance 0.4 meters below ceiling in the centre of each room and each corridor part.

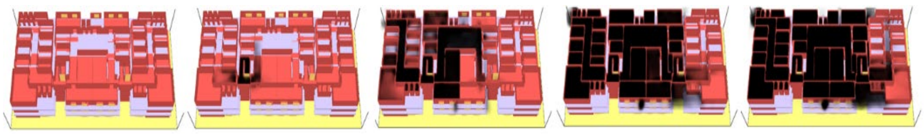

Fig. 4. Smoke flow simulation, as presented in Smokeview visual interface, on the third floor of the building at five different times, each separated by 200 seconds.

In Unity, particle effects and collider object components were used to give the smoke a nice visual appeal. However, the real case simulated in FDS revealed propagation times of up to 30 minutes between parts of the building, which was excessive for a game limited to a few minutes game play. Thus the laws of physics were purposefully broken and the smoke was forced to move ten times faster in order for it to reach the player at the predetermined locations mentioned above. The complete process is fully described in Niinikorpi's work [22]. In the game, the player died when staying over 20 seconds under a CO concentration higher than 6000 ppm. The player was informed in the game about the health risk due to the inhalation of smoke by adding red colour to their peripheral vision, which increased or decreased according to CO's ppm value. Heart beat sound was also dependent on the CO concentration. However, it might be that the values used to model the death in the game do not match those of real cases.

4 Data Collection and Analysis

A total of 169 test subjects participated in the research between Dec 2018 and Feb 2019. The participants were divided in target groups 1-4; *children* were 14-year-olds, *young adults* were university students, *adults* were office workers and *firemen* were fire safety workers at industry or communal fire departments. The recruitment took place through personal relations. Participants were not rewarded. The test conductor avoided any mentioning or wording related to fire, safety or smoke flow to the subjects of the first three target groups as part of the communication protocol.

The important actions of the player in the game were recorded based on the predefined metrics, N1–N19 (Table 1). Metrics were designed based on discussions with fire safety professionals and readings from related literature, and they were saved by the programme on *.csv files. User experience and player demographics were collected immediately the player ended the game, but still using the VR display and controller. Questions Q2–Q5 asked player's subjective opinion about the effectiveness of the game in the fire safety domain, while questions Q6–Q9 investigated experiences related to the game play. The answers to questions Q2–Q9 were collected with a 5-point Likert scale (Fig. 5). Question Q1 (familiarity with fire safety issues) was answered with a 6-point scale: None, sufficient, satisfactory, good, very good and excellent. Age (Q10) was asked with eight different intervals and gender (Q11) with three options.

After the in-game questionnaire, the participants could still answer a post-test questionnaire with open questions on paper. These questions aimed to extract more information about the effectiveness of the game. The open questions were the following: QQ1) In the game, there was a sudden turn of events brought on by the fire alarm: a) What did you think about the change in the game? b) What positive and/or negative aspects do you feel there was relating to the change in the game? QQ2) Did you know in advance that there would be a fire alarm in the game? QQ3) Describe your thoughts about the spreading of the smoke in the game. QQ4) What was good in the game? QQ5) What was bad in the game?

5 Results

There are small differences between the four target groups (Table 1). Group *children* had the slowest reaction times (N1, N3, N4) and did not make so much eye contact with exit signs and floor plans (N9, N10). *Young adult* performed better, but they died more often than other groups. It seems *adult* group performed the best, with good reactions times and three quarters of players escaping or getting to a shelter. Over 85 % of all participants were in the smoke temporally (N13) and there does not seem to be any clear relating difference between groups. Very few participants taped the door for shelter (N19). Of all participants who escaped, 63% did it by an escape exit door and not the main door. Situation awareness (N1), and time spent to leave the initial room (N2 and N3), show a clear relationship with those who died or survived. Also looking at exit signs and floor plans (N9 and N10) and avoiding smoke (N13) seem to have a relationship with survival chances.

Table 1. Results from the four groups; all, survivors and dead as average percentages.

		children	young adult	adult	firemen	ALL	survivors	dead
Participants (N)		51	34	17	67	169	108	61
N1 Player reacts immediately to the alarm	(%)	47,1	41,2	52,9	59,7	51,5	70,4	18,0
N3 Player doesn't leave the room within 20 sec	(%)	86,3	79,4	70,6	65,7	75,1	67,6	88,5
N4 Player doesn't leave the room within 40 sec	(%)	56,9	58,8	41,2	43,3	50,3	30,6	85,2
N5 Player interacts with NPC after the alarm	(%)	82,4	94,1	82,4	92,5	88,8	88,9	88,5
N6 Player calls 112 to inform about fire alarm	(%)	2,0	5,9	0,0	6,0	4,1	1,9	8,2
N7 Player takes along personal belongings	(%)	2,0	5,9	5,9	1,5	3,0	3,7	1,6
N8 Player takes extinguisher from the wall	(%)	13,7	11,8	5,9	10,4	11,2	11,1	11,5
N9 Player makes eye contact with escape signs	(%)	3,9	20,6	23,5	16,4	14,2	16,7	9,8
N10 Player looks building floor plan in the wall	(%)	27,5	38,2	47,1	59,7	44,4	50,9	32,8
N11 Player takes elevator despite the fire alarm	(%)	2,0	0,0	0,0	0,0	0,6	0,9	0,0
N12 Player changes the wing of the building	(%)	27,5	8,8	23,5	22,4	21,3	27,8	9,8
N13 Player was in the smoke at least temporarily	(%)	86,3	85,3	94,1	88,1	87,6	80,6	100,0
N14 Player founds the blocked escape exit	(%)	17,6	38,2	23,5	41,8	32,0	29,6	36,1
N15 Player exits the building by any door	(%)	62,7	44,1	70,6	62,7	59,8	93,5	0,0
N16 Player exits the building by the main entrance	(%)	27,5	17,6	29,4	11,9	19,5	30,6	0,0
N17 Player exits the building by an escape door	(%)	35,3	26,5	41,2	50,7	40,2	63,0	0,0
N18 Player dies	(%)	33,3	52,9	23,5	32,8	36,1	0,0	100,0
N19 Player tapes the door with tape (shelter)	(%)	3,9	2,9	5,9	4,5	4,1	6,5	0,0

The averaged results of the UX questionnaire, questions Q2–Q9 based on all participants, are presented in Figure 5. Overall, over 70 and 80% agreed that the game was effective to remember and to understand fire safety issues (Q3, Q4) and over 60% declared that VR could be more interesting than traditional methods to learn fire safety (Q5). Regarding enjoyment, playability, truthfulness and immersion (Q6, Q7, Q8, Q9 respectively), over 60% in all groups rated them positively. Less than a half of the respondents felt they learned something new (Q2).

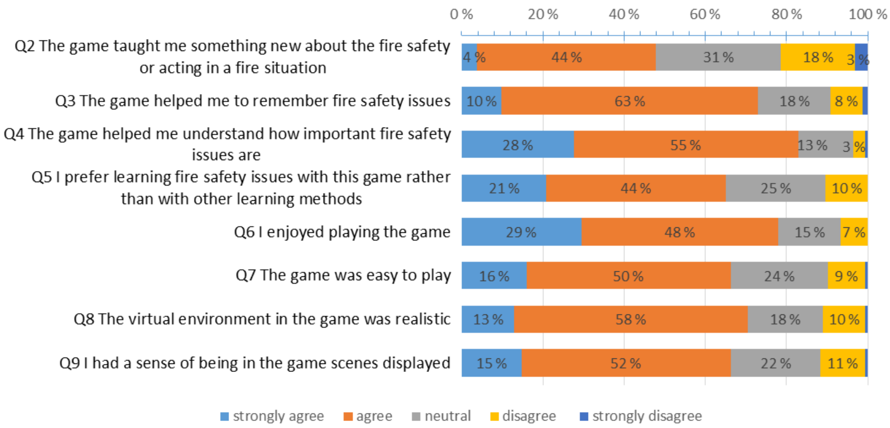

Fig. 5. Subjective measures of player experiences in UX questionnaire.

What comes to the open question QQ1-a regarding player thoughts on the shift in the game dynamic brought on by the fire alarm, the responses could be roughly categorized as follows: added motivation (feeling excitement, surprise, amazement or felt the turn was realistic), non-clarity (in-game or due to real world aspects), wish to act (continuing original task, escaping) and miscellaneous positive answers. In other words, the only negative comments had to do with the fire alarm being not noticeable enough to motivate a complete behavioural change in-game, or the Hanoi Towers task was too interesting to be stopped.

6 Discussion

From a game design perspective, it is important to keep in mind that a change in game objective(s) is the most fundamental change that can occur while playing, as all games are at a basic level defined by what the players are aiming to do within their context. This means that the threshold for misunderstandings is low. In other words, extra attention should be paid into making sure that the engagement of a player is enhanced rather than diminished after a major shift like the one described here.

An example of this was the wave file we used for the alarm signal. The sound sounded a bit too much electronic, and some players had difficulties to make the relationship between the audible signal and the fire situation. Some players commented afterwards that first they thought the sound to be more related to the cognitive task they were performing. Others thought that perhaps the origin of the sound was from outside the game. This could have affected metrics N1, N3 and N4 and explain why subjects did not escape faster. The players that did interpret the sound like intended, however, found the change in the game dynamic to be a positive one. According to open question QQ1a in the second UX questionnaire, the shift was described by many as being for instance exciting, amazing or realistic. All of these descriptions can be seen to directly add to the motivational aspects and thus boosting the experiential side of the game, resulting indirectly in increased interest towards fire safety. These aspects are immediately visible in how an active reaction to the fire alarm seems to have had a positive impact on the possibility of survival. As the previously mentioned metrics N1, N3 and N4 indicate, survival percentages are better because of quick action after the fire alarm was triggered. Many participants could survive despite they entered the smoke temporally. Only 12% of players succeeded to avoid smoke altogether. This fact would be alarming, if not for the fact that some players did it voluntarily, or that they were forced because the smoke was programmed to reach them if they were not fast enough to leave the building. Serious games on fire safety need to ensure that purposefully wrong actions are not interpreted in the analysis of the learning experience in a misleading manner. Thus the future versions of this type of game need to check aspects like this for example right after game play.

The effect of the in-game surprise of a sudden fire alarm is that the game is practically usable only once per player – at least for the purpose of efficient data collection on realistic responses. The second playthrough would necessarily be a very different experience, but maybe with a little bit more potential for teaching specific things about the expected behaviour regarding actual fire situations. This is something that makes the VirPa game a unique tool – it enables the primary function of looking at as authentic behaviour as possible within a highly controlled environment. The smoke flow did not follow the laws of physics exactly. Propagation was calculated with FDS, making the patterns realistic, but in such a big building, the time between the fire starting in the basement and smoke finally arriving to the third floor is about 30 minutes, which is too long for a game of this kind. The length of the game experience was set to a maximum of ten minutes. In other words, the speed of smoke flow was multiplied by 10. It was justified in this case to make a temporal jump forward to force the player to react to the fire event.

As previously mentioned, there was an inconsistency in the location of smoke points in FDS (separated sometimes by 10 meters) and the teleporting spots in VR (separated sometimes by 3 meters). That had an effect on too radical changes in smoke concentration between teleporting points close to each other. The impact was not typically significant, but the issue should be fixed in all future projects. A fast analysis of gathered subjective opinions of participants – Q8, Q9 and QQ3 from the UX and paper questionnaires – proved that participants considered the smoke both realistic and immersive. Another potential concern, however, were the visual elements used for the representation of smoke in players' eyes, both at close and across far distances. In Unity, we used collider and particle effects to make smoke visually appealing. The follow-up project would benefit from further research to optimize the relating input settings of our model or others.

7 Conclusion

This paper presented a serious game applying VR technology. Our research aimed to prove that VR is a suitable tool for communication relating to fire safety. Most of previous works have focused in communication as a way to teach the actions that people should perform in fire situations. In this work, by contrast, we interpreted communication also the other way around, as the process of obtaining and analysing information related to human reactions. The research study focused on collecting data related to human reaction to the game, verifying our initial hypothesis related to communication and pedagogical potential. Our results seem to also indicate that playing serious games is potentially a sound tool for raising awareness of fire safety issues and perhaps for enhancing the skills and knowledge of the players. Especially the hidden agenda regarding the study protocol and the change of dynamics in-game seems to have had a positive experiential effect. It is, however, not possible to claim based on this study, to what degree the players will be able to utilise their VR experience in the future in the case of a real fire situation. The complete results, for example on user experience, will be presented in a future paper.

The visual content of the VirPa game was realistic and the fire scenario provided an enjoyable learning experience to the participants. The game could clearly communicate to the players that they should pay more attention to fire safety issues. In this regard, the game was a success and could raise the awareness among people about sudden cases of fire and fire safety in general. In the future, it would be interesting to measure the final learning experience with a follow-up study.

Indeed, the paper generated various research questions for further studies. Technology industry is intensively seeking innovative safety training solutions, which makes it logical to develop gamified applications for complex physical learning environments like ships' engine rooms or production lines. More generally, the possible parallels that can or cannot be drawn regarding behaviours in a virtual and the real-world context require further study. Be that as it may, looking into this relationship should have a direct impact on the modes of data gathering and its interpretations as well as basic game design.

Acknowledgments. The project was funded by Finnish Fire Protection Fund (PSR) and Turku University of Applied Sciences. We really appreciate the support of the funding agency, PSR, the personnel of Southwest Finland Fire Service, Mikko Helasvuo, Pyry Vuorela, and the Turku Game Lab crew: Oskari Tamminen, Sami Laukkanen, Joshua Kennedy, Aleksandr Osipov, Joonas Törmänen, Antti Lindsten, Joakim Rantala, Lassi Niinikorpi, and Lasse Pouru.

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