Serious games for training occupants of a building in personal fire safety skills

Luca Chittaro and Roberto Ranon
HCI Lab, Dept. of Math and Computer Science,
University of Udine
Udine, Italy
http://hcilab.uniud.it

***Abstract*—** To survive a fire, occupants of a building have to be able to evacuate the structure before the situation becomes unsustainable. Evacuation time is thus a critical factor, but lack of knowledge about the basics of fire safety can dangerously increase this time and also result in various forms of unsafe behavior. In this paper, we propose serious games as a tool to acquire personal fire safety skills, also discussing a specific game we have developed.

Keywords - serious games, fire safety, training, virtual worlds, virtual environments

I. Introduction

Last year, in the US alone, 3000 civilians lost their lives and 15350 were injured as the result of structure fires [1]. And, adjusting for population, the fire death rate (i.e., the number of fire fatalities per million population) of some former USSR countries such as Latvia, Estonia and Russia is about ten times higher than the fire death rate of the US [2].

To survive a fire, occupants have to be able to evacuate the structure before the situation becomes unsustainable. Evacuation time is thus a critical factor and the available fire engineering guidelines make recommendations to reduce it through a proper design of the structure as well as the evacuation aids (alarms, signs,…) it provides to occupants.

Besides the engineering decisions taken in the design of a building, occupants' behavior is another important factor that significantly affects evacuation time. As pointed out by [3], the so-called "panic" reactions are rather atypical of human behavior in fire, and people in fires appear to apply rational decision making in relation to their (typically limited) understanding of the situation. The lack of knowledge that people have on fire development and the dynamics of a fire emergency do not prepare them to have the best response during fires. Therefore, clearly knowing in advance proper fire safety behavior is a personal protection strategy that would allow each occupant to significantly increase her chance of survival by reducing evacuation time as well as preventing common fatal errors that occupants make due to lack of knowledge. Previous training is important because stress and negative affect in a real emergency prevent creative thinking and generation of proper procedures on the fly. Moreover, stress combined with lack of knowledge about suitable behaviors produces in some occupants a "cognitive paralysis" phenomenon, where people do not take any action at all, leading to fatalities in otherwise survivable conditions [4][5].

In this paper, we propose serious games as a tool to acquire personal fire safety skills. First, we will provide motivations for adopting serious games in this domain. Second, we will describe in detail the game we have developed. Third, we will show how data logged by the game can be used for player's behavior analysis. Finally, we will discuss future work.

II. SERIOUS GAMES FOR FIRE SAFETY TRAINING

A. Traditional approaches for providing occupants with fire safety knowledge

Although the problem of informing occupants of a (public) building about fire safety and evacuation procedures is usually acknowledged, and at some degree (variable from country to country) is mandated by law, current approaches to providing people with that information tend to be based on two main solutions:

- Written instructions posted on walls (e.g., the floor plan and fire safety guidelines one typically finds on hotel doors) and signs (e.g., "Do not take this elevator during a fire!").
- Evacuation drills at the workplace.

Long, written instructions, posted on doors and walls are not necessarily read by occupants, and even if they are, there is no guarantee that a single reading will allow the occupant to remember them during an emergency. Moreover, stress during a real emergency creates the so-called "tunnel vision" phenomenon in which people's attention narrows to only a very limited number of details, usually at the center of the field of view [6]. This phenomenon can leave signs unnoticed by the occupant, and can be exacerbated by suboptimal visibility conditions (e.g., insufficient illumination or smoke), sign design or sign placement.

Evacuation drills may not be mandatory and thus never be carried out in some countries. In other cases, they tend to be carried out very rarely (because organizing them has a cost, carrying them out results in lost work hours, and employers may also be worried that someone could get hurt in the drill) and it is thus unclear if the knowledge acquired could be sufficiently retained to be of use in a future real emergency. Moreover, an evacuation drill concentrates on a specific scenario and does not give occupants the possibility to familiarize with all the possible routes from different starting positions and with the possible different locations of the fire.

Finally, in some public buildings like airports, the occupants can be totally unaware of the topology of the building or the location of the emergency exits and they have not received any training in evacuating such buildings.

B. *Motivations and benefits of serious games*

A few proposals of game-based training systems deal with fire safety topics (e.g., [7][8][9]), but they are aimed at professional training of first responders such as firefighters, so the training goals and the procedures taught are inappropriate for the target user we are considering in our work, i.e., any citizen with no prior knowledge about fire safety who needs to learn the basics to survive a fire in a building. Some preliminary research on simulating building evacuation with the Unreal game engine has been carried out by Mól et al. [10] but is limited to allowing a user to simply move inside the 3D model of the building, does not model fire scenarios and does not contain pedagogical knowledge.

To teach personal fire safety skills, a serious game can immerse the user in fire emergency scenarios, where the goal of the game is to survive the fire and player's survival is strictly dependent on choosing the right actions in evacuating the building and taking as less time as possible to complete the evacuation, while staying as far away as possible from danger. To succeed and progress in the game, users would need to improve their decision making in fire situations, learning to avoid common occupants' errors.

A serious game could be a more effective solution than reading materials or evacuation drills for motivating people to train in personal fire safety. Unlike those approaches, a game could be fun and engaging and people could thus want to play it at home outside working hours. This could increase exposure time to personal fire safety content, and promote repetitive rehearsal of safety procedures, which improves retention of knowledge. Moreover, a game could provide personalized advice based on users' errors and, unlike evacuation drills, the game simulations are available anytime all year long.

A serious game approach to fire safety could also make employers less reluctant to support evacuation training initiatives. Unlike evacuation drills, a serious game would not lead to disruption of the company daily activities or the possibility that someone could get hurt as in a real-world simulation.

The game could take place in a virtual environment based on fictitious buildings or virtual reproductions of the actual players' workplace. In the first case, the game can teach useful knowledge that applies to any fire emergency (e.g., how to deal with smoke, recognizing and following emergency signs, avoiding elevators, …). In the second case, the increased cost of modeling a real-world building would result in added value, because the game would then also let people familiarize with the different escape routes available in that specific building and also learn to choose the best one according to the different possible emergency scenarios (e.g., the location of fire and smoke with respect to current occupant's location).

From a cognitive point of view, this approach would allow the user to acquire different types of spatial knowledge [10] [12]: landmark, route, and survey knowledge. These types of knowledge account for people's navigation abilities in a building and form spatial cognitive maps of the environment. From this perspective, the serious game experience could help users build richer cognitive maps. For example, as discussed by [13], the frequent real-world prohibition of using the alternate exits during non-emergency conditions limits the formation of cognitive maps and inadvertently creates negative associations and biases, highly limiting the likelihood of their use in emergencies. The author explicitly proposes training and education to reduce this problem.

Finally, another advantage of serious games is that players' actions can be logged for de-briefing purposes as well as more general analysis of the behavior of several users. This broader analysis could reveal frequent behaviors of occupants that point to actual deficiencies of the real building. For example, noticing that many occupants do not take the most obvious emergency exit the first time they are challenged with a given situation could lead to investigate that exit in the real-world (e.g., it could be placed in a scarcely visible position, the signage could be insufficient or incoherent, and so on).

III. THE EVACUATION GAME

The game we developed aims at reproducing situations in which typical occupants of our university building (professors, students, administrative staff) might find themselves in case of fire emergencies. In the following, we first illustrate the main design choices we made, and then describe the game features and behavior.

A. *Design choices*

When designing the evacuation game, we had three main goals in mind:

- immerse players in scenarios that reproduce as close as possible the experience of being in a real fire;
- create engagement and motivation to play;
- teach personal fire safety skills, both general and specific to the university building; promote creative thinking and rapid response to unexpected situations.

With respect to the first goal, a natural choice was to employ 3D graphics with a first-person view. More specifically, the game reproduces:

- the spatial configuration and appearance of the university building, composed by three floors each one containing about 100 rooms;
- phenomena and objects directly related with fire emergency and evacuation, such as fire, smoke,

emergency exits, emergency signage, alarm buttons, as well as related sounds, such as aural alarms.

- common objects in offices and laboratories, such as computers, telephones, documents, suitcases, car keys. Most of these objects are interactive, i.e., they can be picked up or used, depending on their type.

With respect to the engagement and motivation goal, we decided to:

- organize the game into levels of increasing difficulty. In each level, the player is presented with a specific fire emergency, and her goal is to evacuate the building following emergency signs as well as to perform all other needed actions (e.g., call the university internal safety service, close doors,…), while at the same time avoiding erroneous actions (e.g., taking an elevator, inhaling smoke,…). To progress in the game, the player needs thus to put into practice, in different situations, knowledge about the building (e.g. locate the closest emergency exit) as well as general knowledge about fire safety and evacuation procedures. As the player progresses through levels, a better spatial knowledge of the building and more choices and actions are needed to successfully complete the level;

- introduce scores (which are calculated by taking into account the time taken to evacuate and the right/wrong actions performed in the game) to provide self-assessment of the level of abilities reached and promote competition among players (e.g. coworkers).

The challenge provided by the game is then created both by time pressure (evacuate as soon as possible to survive) and by the need to decide among a number of actions that can be right or wrong depending on the specific scenario.

With respect to the pedagogical goal, we decided not to provide instructions during evacuation scenarios, to make them more realistic and more challenging. Therefore, we organized each game level into three phases: introduction and explanation, evacuation, and final debriefing. The first and third phases are respectively devoted to introduce the player to the scenario and provide detailed explanations of what the player did right or wrong and why. In the following, we describe in detail each phase.

B. Introduction and Explanation Phase

This phase introduces the player to the evacuation scenario. First, the game presents the information that will be useful in the scenario (e.g., collect some important objects before evacuating, close doors behind). If the player chooses so, the game can also provide a full explanation of all rules and procedures to be followed in case of fire. These rules have been acquired through interviews to the internal safety service of the university.

Then, among a set of game characters, the player chooses the one that is closest to her in terms of age, gender, and weight. This choice will influence the running speed and strength of the character during the game. Currently available characters include students (male and female) and professors (male, female, different ages).

C. Evacuation Phase

In this phase, the player enters a scenario and tries to fulfill the assigned goals. Goals are deliberately generic (e.g., "take important objects with yourself") since we want the player not just to perform a predefined sequence of actions, but to reason about what needs to be done at each moment to learn how to adapt to the different scenarios she might encounter. At present, we have implemented three scenarios covering common fire situations:

- a small fire in the player's office caused by the explosion of a computer battery (see Figure 1). The player must pick up some objects, exit the office, alert the university internal safety service and decide if it is appropriate to activate the fire alarm;

- fire and smoke in a lab close to the player's office. The player must alert the regional Fire Department, decide if it is appropriate to activate the fire alarm and to take possible important objects with her, then evacuate the building;

- ringing of the warning alarm (which is characterized by a non continuous sound the player should familiarize with), then smoke entering into the player's office and ringing of the evacuation alarm (continuous sound). The player should decide if she should take possible important objects with her and then evacuate the building.

The player starts from the first scenario, which is the less complex one, and then, if she is successful, can proceed to the next one.

The game interface shows the environment from a first-person perspective (see Figure 1 and 2) and also indicates elapsed time (top center of Figure 1) and character's strength level (bottom left of Figure 1). The player controls her character by using the mouse to orient the field of view (with the associated walking direction) and arrow keys to control movement. Following typical game conventions, modifier keys allow the player to walk, run and jump. Her walking and running speed, as well as the jumps she can made, are determined by the age, gender and weight of the character. For the current version of the game, walking, running and jumping abilities have been empirically determined by actually measuring how fast some persons (with physiological features close to the available characters in the game) were able to move in the real building.

Possible actions on an object are highlighted when the cross in the center of the screen (see Figure 1) is positioned over the object, and are performed by pressing the mouse left button. They include:

- pick up objects, e.g. keys, documents, suitcase, umbrella,…;

- press buttons, e.g. activate alarms (see Figure 2), elevator buttons,…;

- open and close doors and cabinets;
- make telephone calls.

When the player activates complex actions (e.g., making telephone calls), the game displays a multiple-choice menu that allows her to choose among different sub-actions (e.g. number to call, choice of possible sentences to say). We have also carefully modeled the duration of actions such that they take the same amount of time they would require in the real world (e.g., in a telephone call, the player hears herself and the called person speaking the actual dialogue).

The player can complete the scenario by successfully evacuating the building, reaching the outside or a safe zone, or die because her strength (see bottom left part of Figure 1 and 2) has decreased to zero. Strength decreases over time depending on the amount of fire and smoke surrounding the player's character (i.e. the closer and the longer the player's character is in a damaging situation, the quicker its strength drops to zero). The rate of decrease is also influenced by the character's age, gender and weight.

D. *Final De-Briefing Phase*

In this phase, the game reports about the success or failure of the player, the time required to play the scenario, and the correct and wrong actions, also explaining why they were deemed correct or wrong. This includes whether the player has followed the right route to evacuate the building (i.e. she has chosen the shortest path to the exit that allowed to stay as much as possible away from fire and smoke).

To each fulfilled or missed goal, the game associates a score (depending on its importance in the particular scenario) which is totaled to form a global score for the scenario. While this is not strictly important for the game objectives, it helps the player compare different runs of the game or compare her performance with other players, thus encouraging improvements.

IV. IMPLEMENTATION

The game has been implemented using the NeoAxis game engine (www.neoaxisgroup.com). NeoAxis provides a set of visual tools that enable the developer to build game level maps, define interactive behaviors for objects, and manage the 2D interface of the game. NeoAxis uses Ogre (www.ogre3d.org) for rendering and supports NVIDIA PhysX or ODE for collision detection and physics simulation.

The university building, as well as all the objects, have been modeled in 3D Studio Max and then have been imported into the NeoAxis map editor, where we have arranged all objects into the environment and defined their interactive behaviors through .NET code scripts. For example, to check whether the player has followed the optimal route to the exit, we have defined a set of box-sized, invisible checkpoint regions in the map, and we check through scripts when the player enters or exits each region. The optimal route for each scenario is therefore defined as the sequence of contiguous regions that go from the player initial position to the closer exit, and are as much distant as possible from fire and smoke. Analogously, the influence of fire and smoke on the player's strength has also been modeled using box-sized invisible regions. Whenever the player is in one of such regions, her strength is decreased according to how much the region is filled with fire or smoke, also considering the character's physiological features. Finally, fire and smoke have been visually modeled by using billboards, animated textures, and particle systems, which are all features natively provided by the adopted game engine.

V. ANALYZING PLAYER'S BEHAVIOR

To carry out off-line (i.e., post-game) analysis of players' movements and navigation, we have integrated the serious game with the *VU-Flow* tool we have described in [14]. *VU-Flow* is able to produce interactive visualizations of users' behavior in a virtual environment, allowing an analyst to answer questions such as comparing the navigational behavior of two (or more) users or discover the areas that are more traveled overall. More specifically, VU-Flow post-processes movements logs recorded during users' interaction sessions, and then visualizes users' navigation over a 2D map of the virtual environment using two categories of visualizations:

- *non-aggregated visualizations*, aimed at highlighting navigation patterns of individual moving entities, e.g., to compare navigation patterns of two individual users. Data belonging to different moving entities are highlighted separately over the 2D map, e.g. using colored trails;
- *aggregated visualizations*, aimed at highlighting a population's navigation patterns, e.g., identifying more traveled areas in the virtual environment. In these visualizations, data belonging to different moving entities are first aggregated, and then visualized over the 2D map.

The analyst can then interact with the visualizations to focus on a particular user, or group of users, or period in time, or area of the virtual environment.

To integrate the serious game with VU-Flow, we had to: (i) add code to the NeoAxis game engine to produce logs of player's movements (in the format described in [14]), (ii) extend VU-Flow in such a way that it is able to handle multiple floors simultaneously.

As a preliminary study, we carried out a post-game analysis of the behavior of 7 players, who played all three game levels. All recruited players work (since at least 2 years) in the university building, their offices are at the second floor, and they have never participated before to an evacuation drill, either real or virtual. They are all familiar with 3D videogames, with varying degrees of experience. In the following, we describe some examples of the insights that post-game analysis allows to obtain.

Figure 1. The first level: a small fire involving the player's computer.

Figure 2. An alarm button in the building.

A. *Aggregated visualization example*

Figure 3 shows a screenshot taken from the analysis of all players' behavior in the first scenario of the game. In particular, it focuses on the area of the second floor that contains players' movements and highlights those places the players spent more time in, using a blue-red temperature scale. One can easily notice that on average players spent more time in the office where the game started: the first red spot in the office corresponds to the starting position where the player initially perceives the environment where she has just been immersed, the second red spot corresponds to the office door area, where the player has to control her movement more carefully to successfully go through the door (which was open). After going out of the office, there is an area where players briefly stopped, presumably to take a decision about which way

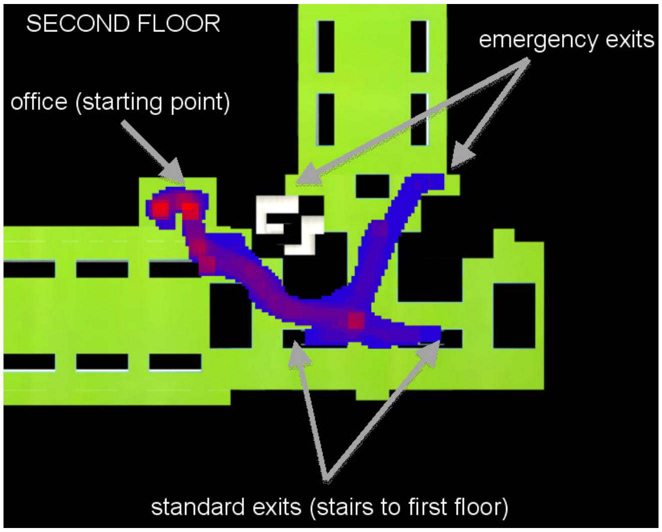


Figure 3. An aggregated visualization of player's behavior

to go. Then, all players navigated up to reaching an area close to the two (non-emergency) stairs that lead to the first floor. Finally, the players split into three groups: the first group took one of the (non-emergency) stairs, the second took the other, while only the third group followed emergency exits signs, taking one of the emergency stairs that lead outside more safely and in less time.

One of the details of this visual analysis that attracted our attention was that all players in the third group went straight to the emergency exit which is on the right of Figure 3, without noticing the slightly closer emergency exit on the left. We thus went through their path in the real world and found a visual access problem in the actual building. Unless one does not look around herself very carefully, which is unlikely under stress, the left exit is extremely difficult to notice: as shown by the photograph in Figure 4 (which was shot from the point where in the game most players stopped near the stairs), there is a column on the left that occludes the view, and the only clearly visible emergency sign is above the right exit and points to it. Thus, analysis of game players' behavior highlighted an issue that is actually present in the real building and could be relevant to the internal safety service, especially for a crowd evacuation where the current positioning of emergency signs might address the entire flow of people toward the right exit, while having people use also the left exit would reduce congestion and improve global evacuation time.

B. *Non-aggregated visualization example*

Figure 5 shows a screenshot taken from the analysis of all players' behavior in the second scenario of the game. The visualization gives a clear picture of different navigation strategies, by drawing each player's path in a different color. The scenario starts at the third floor (left image in the figure) inside an office (marked A in the figure). As one can immediately notice, all players except one chose to go towards the area in the upper part of the figure. Since the non-aggregated visualization allows to know who each player is, it

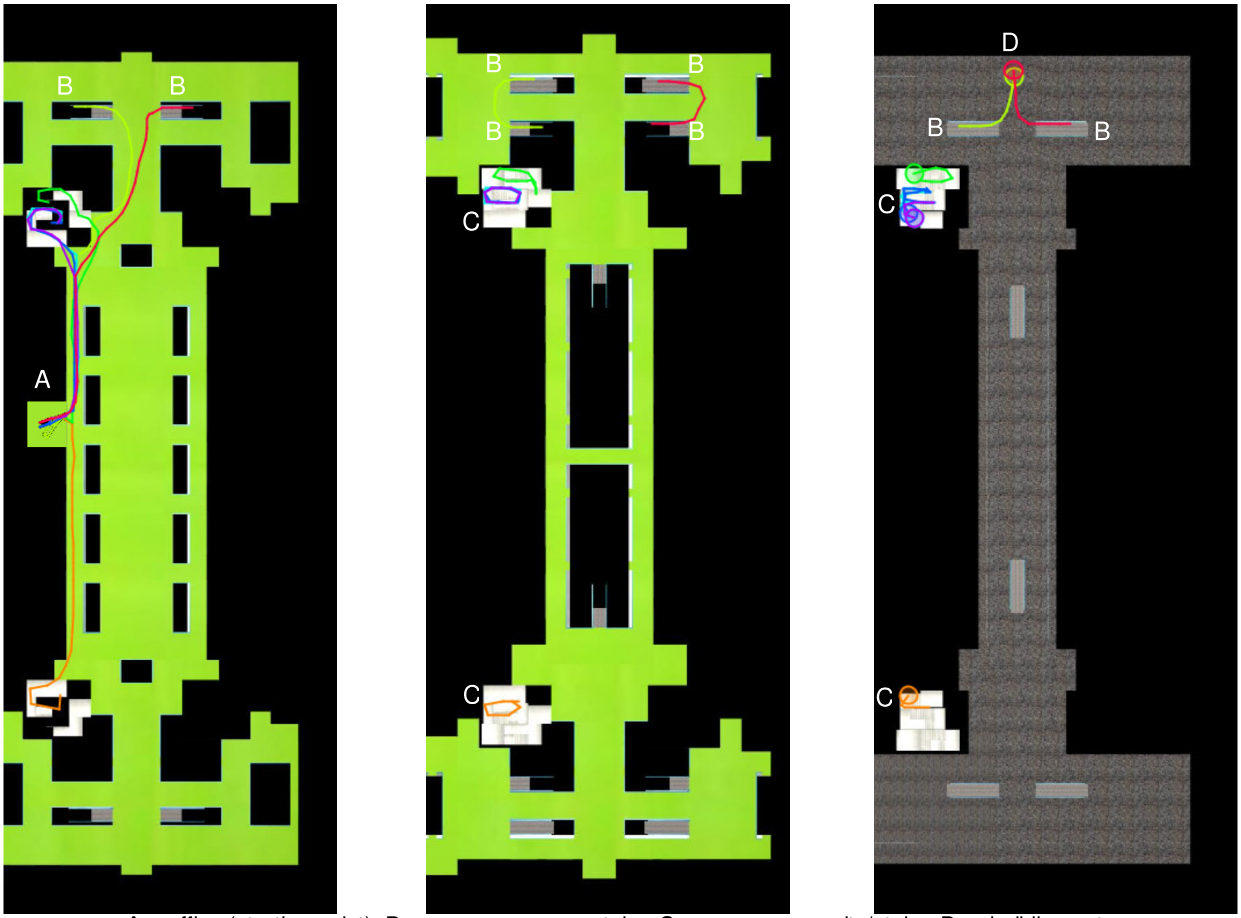
Figure 4. The identified visual access problem in the real building

was possible to learn that the player who went towards the lower part showed this behavior consistently also in the other scenarios, probably because his actual office is located in that area and he instinctively went to set himself in the most familiar situation. Of the 6 players who went towards the upper part, one can easily notice that 2 went through a longer path that lead them to exit through the main building door, marked D in the figure (this is the path they follow every day to exit the real building), while the other 4 took the closest emergency stairs: more specifically, 3 of them took the closest door of those stairs, while one did not notice that door and took an alternative one.

C. *Players' feedback*

After they played the game, we informally interviewed each of the players, getting several comments about the game experience as well as some suggestions of desired features. The main issues that were reported (by two or more players) are:

- complaints about character's speed, which was not as high as the one they are used to obtain with recreational games. This is an example of how previous experience with recreational games can make some necessary features (in this case, a physically correct locomotion speed) detrimental to the engagement in the experience. This issue has another side too: the players who complained actually believed to be able to move also in the real building much faster than what is actually allowed by their age, weight and physical fitness. This is consistent with the known tendency of people to underestimate evacuation time (especially the time spent in stairwells) and suggests that experience with recreational games (and their often unrealistic locomotion speeds) could reinforce these wrong expectations.
- need to understand better how much heat the character is exposed to. One player suggested to highlight the



A = office (starting point); B = non-emergency stairs, C = emergency exits/stairs; D = building entrance

Figure 5. Analyzing each player's trajectory through a non-aggregated visualization.

heat areas with semi-transparent volumes of different colors, two others suggested to give audio feedback by reflecting the effect of heat on the character's breathing sounds.

- need to increase the emotional intensity of the game. Two players mentioned that the game should take stronger steps in creating stress and anxiety in the player. They mentioned examples taken from their experience with recreational games, referring in particular to the use of frightening sounds (human screams, structures cracking,…). From this emotional perspective, three players reported that they were impressed by the scenario that contained a significant presence of smoke, because it made them think about how it would be frightening in the real building.

VI. Conclusions and Future Work

In this paper, we have advocated a serious games approach for training the occupants of a building in personal fire safety skills. The game we have developed focuses not only on having players acquire the navigational knowledge required to evacuate a building, but more generally allows them to learn and practice, in a variety of different situations, some of the actions and procedures that are required in fire emergencies.

In designing and developing this serious game using one of the available general-purpose 3D game engines, we encountered a number of limitations of such engines, which we plan to overcome in future work. First, the models we currently use to control character speed and loss of strength due to smoke and fire are too simplistic. We believe that a serious game engine should be provided with physiologically sound models of human activities, ideally with the possibility for the player to personalize these models based on her personal data. It could be also interesting to demonstrate the effect of the personalization before starting to play scenarios, so that players could familiarize with the differences their character will show with respect to typical recreational games. Similarly, physically and visually realistic simulation of smoke and fire phenomena could also greatly improve the fidelity of the game to real fire emergencies as well as its visual attractiveness and emotional effect (which could increase motivation to play).

Another topic of future work concerns how to make the player more aware of the physiological state of her character (e.g., strength, injuries,…) and the environment (e.g., heat, highly toxic smoke,…) in the game. This requires a careful exploitation of visual and audio cues. In numerous games such demonstrations have been achieved e.g. by darkening images, inability to perform precise movements, shaking display, etc. The same kind of feedback may be used to simulate loss of consciousness as a result of toxic fumes.

We also plan to extend the analysis we outlined in the previous section and perform more formal user studies. In particular, we will proceed along three main directions:

- Engagement. We would like to evaluate how much and in what ways the game is able to involve the intended players. To do so, we plan to derive and employ a questionnaire from recent proposals that have focused on measuring immersion [15] and enjoyment [16] [17] in games.
- Effectiveness. We would like to evaluate if the players acquire and retain the knowledge provided by the game. This will be initially done inside the game, by presenting users with new scenarios to check if they apply the knowledge they have been exposed to in previous scenarios. Then, after some months, we will present players with scenarios they have already played to check if they remember the procedures they had learned.
- Transfer. We would like to evaluate how much the knowledge acquired in the game transfers to the real world. To do so, we will organize live simulations of a few game scenarios in the real building. The dangers will be represented through scenographic mock-ups placed in the same locations as in the game, and players will be asked to reach in the real building the same objectives of the game.

Finally, we plan to experiment with multi-user game levels. In this case, besides the obvious advantage of generating more realistic situations, the scenarios could also consider different roles for the players (e.g. workers, company safety officer,...) and interesting insights could come through the congestion analysis functionality provided by the VU-flow tool.

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