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Serious Games as a Behaviour Elicitation Tool:
Applications to Evacuation Scenarios

by

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Abbreviations

2D	Two-dimensional
3D	Three-dimensional
ABM	Agent-Based Modelling
ABMS	Agent-Based Modelling and Simulation
ABS	Agent-Based Simulation
AI	Artificial Intelligence
ANPC	*Autoridade Nacional Proteção Civil*
AOA	Angle of Arrival
ASET	Available Safe Egress Time
AT	Activation Time
BDI	Beliefs, Desires, Intentions
BIM	Building information Model
CA	Cellular Automata
CAD	Computer Aided Design
CAVE	Cave Automatic Virtual Environment
CCTV	Closed-Circuit Television
FD	Fire Drills
FEUP	*Faculdade de Engenharia da Universidade do Porto*
FOSS	Free and Open-Source Software
FPP	First Person Player
FPS	First Person Shooter
GUI	Graphical User Interface
HMD	Head Mounted Display
HRR	Heat Release Rate
LIACC	*Laboratório de Inteligência Artificial e Ciências da Computação*
LNEC	*Laboratório Nacional de Engenharia Civil*
MARIE	*Modelo de Análise de Risco de Incêndio em Edifícios*
MAS	Multi-Agent Systems
MT	Movement Time
NASA	National Aeronautics and Space Administration
NFPA	National Fire Protection Association
NIST	National Institute of Standards and Technology
NPC	Non-Player Character

PBD	Performance-Based Design
PET	Pre-Evacuation Time
PDA	Peer Designed Agents
RFID	Radio-Frequency IDentification
RPG	Role-Playing Game
RSET	Required Safe Egress Time
SD	Standard Deviation
SFPE	Society of Fire Protection Engineers
SG	Serious Games
SPEED	Simulation of Pedestrians and Elicitation of their Emergent Dynamics
SPSS	Statistical Package for the Social Sciences
TDOA	Time-Difference of Arrival
UWB	Ultra Wide Band
VE	Virtual Environment
VR	Virtual Reality

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"We can only see a short distance ahead,
but we can see plenty there that needs to be done."

Alan Turing

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Abstract

This thesis proposes the use of Serious Games as a behaviour elicitation tool in addition to the traditional methods such as direct observations or stated-preference questionnaires. The resulting knowledge is needed to improve behavioural models of intelligent agents mimicking pedestrians. From the literature review and subsequent gap analysis, a methodological approach was envisaged leading to the Conceptualisation of a novel methodology for human behaviour elicitation coined SPEED (Simulation of Pedestrians and Elicitation of their Emergent Dynamics) aimed at revealing human behaviour and capturing the complex activities of pedestrians in the real world. As a case study, the behaviour of pedestrians when searching the best path to exit from a building was chosen. Building egress, or evacuation, has gained increasing interest by the research community, with important implications to architecture and building management, related to safety. Stakeholders, including architects and fire engineers, need simulation tools to validate building safety, namely evacuation simulators. The agent-based evacuation simulators, although attempting to implement some sort of intelligence into the agents mimicking humans, lack realism and knowledge on behavioural aspects related to humans. SPEED proposes to address this problem, using Serious Games. A set of experiments conceived with the help of an international expert panel, based on the Delphi method, were put up to test the methodology. After a pilot test, three experiments were made using Serious Games and questionnaires. The results were statistically analysed evidencing the subjects preferences and applied into an agent-based simulator developed using NetLogo. These agents were modelled by using the peer-designed agents (PDA) concept that emerged recently within the artificial intelligence community. The SPEED approach can be used for knowledge elicitation of pedestrian behaviours in other contexts, besides egress, within social simulation, based on the PDA concept.

Keywords: Agent-Based Modelling and Simulation, Behavioural Modelling, Behavioural Elicitation, Serious Games, Evacuation Scenarios.

Resumo

Esta tese propõe a utilização de Jogos Sérios como ferramenta para eliciação comportamental, em complemento a métodos tradicionais tais como observação direta ou questionários de preferência declarada. O conhecimento resultante é necessário para melhorar modelos comportamentais de agentes inteligentes que simulam pedestres. A partir da revisão bibliográfica e subsequente análise de lacunas científicas, foi concebida uma abordagem metodológica levando à conceptualização de uma nova metodologia para a eliciação do comportamento humano denominada SPEED ([acrónimo derivado do inglês] *Simulation of Pedestrians and Elicitation of their Emergent Dynamics*) tendo por objeto a eliciação de conhecimento sobre o complexo comportamento das atividades dos pedestres no mundo real. Como caso de estudo, foi selecionado o comportamento de pedestres na procura de melhor caminho para durante a evacuação de edifícios. Este domínio, relacionado com a segurança dos ocupantes de edifícios, tem sido alvo de um interesse crescente da comunidade científica, tendo implicações importantes na arquitetura e gestão dos edifícios. Arquitetos e engenheiros necessitam de ferramentas de simulação para validar a segurança de edifícios, designadamente através de simuladores de evacuação. Os atuais simuladores de evacuação baseados em agentes inteligentes, carecem de realismo e conhecimento relacionado com o comportamento humano. A metodologia SPEED propõe o uso de Jogos Sérios, para fazer face a este problema. Foi concebido um conjunto de experiências, com o apoio de um painel internacional de especialistas, baseado no método de Delphi, serviram de exemplo para testar a metodologia. Após realizar um teste piloto, três experiências foram executadas usando jogos sérios e questionários. Os dados obtidos foram analisados estatisticamente, evidenciando as tendências dos participantes. Os resultados obtidos foram aplicados num simulador baseado em agentes, o Netlogo. Estes agentes foram modelados através do conceito de *Peer-Designed Agent,* agentes inteligentes modelados a partir dos seus pares. A metodologia SPEED poderá ser utilizada para eliciação de conhecimento de pedestres noutros domínios para além da evacuação de edifícios, em que a simulação social esteja presente, para criação de agentes inteligentes com base no conceito de PDA.

Palavras-chave: Modelação e Simulação Baseadas em Agentes, Modelação Comportamental, Eliciação Comportamental, Jogos Sérios, Cenários de Evacuação.

1. Introduction

1.1 Overview

The evolution of civilization in the last decades has lead to an increasing urbanization. It is expected that by 2025 over 60 percent of the global population will live in cities (Prendinger et al., 2013). This trend has leveraged new developments in building design, both in complexity and size (Purser, 2003; Still, 2000). However, bigger and more crowded cities bring about new problems (Lovreglio et al., 2015), and among them are safety and security (Kim et al., 2012).

Considering threats that cities face, from natural or man-made origin, are earthquakes, floods, terrorist attacks, and naturally fire (Almeida et al., 2014b; Cha et al., 2012; Peacock and Kuligowski, 2004). In order to successfully prevent and respond to such emergency situations, urban planners need proper tools and simulation is one of the most appropriate (Johnson, 2008; Lawson, 2011).

Computer modelling and simulation are amongst the latest developments in safety and security practice (Ronchi and Nilsson, 2013; Smith and Brooks, 2013; Smith and Brokaw, 2008). Scientific evolution and knowledge, allied to the new computational techniques, lead to the creation of new tools helping practitioners and stakeholders to estimate the evolution of emergency situations, forecast damages and casualties, as well as test new prevention and mitigation approaches (Bonabeau, 2002; Kinateder et al., 2014). Amid these, one important aspect is related to the safety of building occupants, namely, the evacuation process that sometimes is a chaotic one (Almeida et al., 2014c).

To help designers and emergency planners, several evacuation simulators were developed recently, mainly over the last thirty years. However the models tend to make over-simplifications especially at the representation of humans, due to the inherent complexity of their movement and decision making process during the escape (Kuligowski, 2009; Still, 2000). Besides the kinematics' aspects, there is a psychological dimension related to human behaviour that is hard to model and simulate. As such, evacuation simulators, although attempting to implement some sort of intelligence into the agents mimicking humans, lack realism and knowledge on behavioural aspects related to humans, which ultimately contributes to producing kind of unreliable outputs with little significance to be used by stakeholders (Zoumpoulaki et al., 2010).

In short, the problem resides in the human behavioural modelling for which there is a lack of knowledge considering the many variables and unpredictable behaviours that people show in both normal and emergency situations (Helbing et al., 2002). This problem affects all pedestrian simulators, not only evacuation simulators, and was labelled one of the greatest challenges of the XXI century (Galea, 2012). It is therefore important to develop behavioural models that can accurately represent and mimic pedestrians, to enhance the realism of the existing simulators.

1.2 Motivation

Artificial Intelligence (AI) techniques, such as Multi-Agent Systems (MAS) are used to tackle the challenges of modelling the abstractions related to human behaviour and reasoning processes, aiming to provide more realistic simulators (Murakami et al., 2002; Pan et al., 2007). Therefore, the issue of how to represent, or model, knowledge using intelligent systems is one of the greatest challenges of modern AI (Pacheco and Garcia, 2012; Russell et al., 2015).

For decision-support systems, for instance, to understand how customers choose products and make decisions, the elicitation of users' preferences is a primary issue for which various techniques may be used (Chen and Pu, 2004). The knowledge elicitation phase of expert system development is considered to be a major hurdle especially as the expert knowledge is multifaceted since it has both explicit and objective knowledge as well as implicit (Crandall, 1989). Of the many techniques available, there is a methodology called "Delphi process" that is used for the elicitation of knowledge from experts of a certain field (Brown, 1968). This method has been used to extract the knowledge of one or more experts with the goal of establishing a set of concepts and facts much needed to feature intelligent agents with (Lawson, 2011).

Crowd incidents in which people are seriously injured or even killed when trying to leave a crowded space or building can occur at sports events, religious gatherings and music concerts (Helbing and Mukerji, 2012; SFPE, 2002). Consequently, crowd management is important in such events and for this reason emergency responders need to have plans of how to deal with crowds in emergency situations (Larochelle, 2009; Moulin and Larochelle, 2010; Oulhaci et al., 2014).

Psychological aspects of human behaviour under stress has been studied in the context of emergency situations for quite some time (Helbing et al., 2000; Sime, 1995). The study of known and well documented disasters, such as the collapse of the World Trade Center in 2001 (Averill and Mileti, 2005) has given some data so as to be used in models. In Portugal, Coelho (1997) has been studying the behavioural aspects of humans in emergency situations trying to identify some patterns that can later be incorporated into the simulation models (Coelho, 1997; Cordeiro et al., 2011a, 2011b).

1.3 Problem Statement

Over the past decades, a lot of research and effort have been directed to the development of evacuation simulators to help designers, authorities, and other stakeholders, on the design of safer buildings. Albeit there are a few dozens of models and simulators, their validation and calibration are rather a challenge. Data is needed to accomplish that effort. One method commonly used for data collection relies on questionnaires, for instance applied to fire drills participants, fire survivors or experts.

Another issue is related to the behaviour of humans in such conditions. Existing simulators lack the recreation of all aspects related to the evacuation process. Studies to understand the reasoning process of humans when confronted with the sound of evacuation alarm, and the tasks they perform before actually starting to seek the nearest exit and proceeding to a safe area, are yet not completely known. As such, more research is needed to fully understand the human thinking process during those crucial moments. Fire drills normally do not address this issue, since they are more focused on the evacuation time, rather than the decision-making process performed upon the evacuation itself.

The problem to which this thesis intends to contribute has two parts:

1) The behaviour of humans during the evacuation of buildings is normally assessed by questionnaires that are presented to the survivors sometime after the events. Another approach is to film and observe Fire Drills (FD) and try to elicit human behaviours from those direct observations as well as from using questionnaires. However these methods present some drawbacks:
    a) During emergency situations such as fires, the observation of persons while struggling to leave the buildings is hardly a priority;
    b) There are not that many fire events or emergency situations to be observed with the adequate means for direct observations;
    c) Questionnaires to survivors present memory bias due to the time that has passed since the event;

   d) In FD it is difficult to get people's attention / commitment and they hardly recreate the emotional ambience of a real situation;
   e) Organizing and implementing FDs requires the mobilization of certain resources, leading to high financial costs;
   f) FDs affect the normal functioning of the site where they take place, interrupting the current activities and thus are run very sparsely;
   g) Sometimes it is not possible at all or it is quite complex to perform FDs in certain locations (e.g. hospitals, communication control rooms).
2) Existing pedestrian simulators lack detailed data on human behaviour in evacuation scenarios. As such, there is a particular need of more knowledge on human behaviour and associated decision-making process performed prior to the evacuation procedures and during the evacuation itself. Nonetheless, some related drawbacks are:
   a) Methods for human behaviour acquisition are costly (e.g. fire drills observations, video images, Virtual Environment, CAVEs);
   b) Virtual Reality systems, such as CAVEs, require expensive resources for implementation and execution;
   c) It is required for test subjects to be present at the research facilities;
   d) Huge data sets and computational resources are needed to infer useful information and knowledge from that data.

In short, the problem identification is two-fold: (1) **the elicitation of human behaviour is normally done by direct observation or by means of questionnaires;** (2) **existing evacuation simulators (and pedestrian simulators in general) still lack data on human behaviour for allowing better modelling of evacuees in emergency situations.**

To overcome the aforesaid problem new elicitation methods for data collection and behaviour modelling techniques are needed.

1.4 Towards a Behaviour Elicitation Methodology

The study of human behaviour often follows one of two possible approaches: 1) collect data from direct observations, surveys, stated preference questionnaires or other forms of data, such as video or still images, and analyse them trying to elicit a model; 2) create a model based on the literature and experts knowledge to simulate its dynamics and gain a better understanding on the complex dynamics of the human decision-making process. The former approach is supported by the theory of agent-based models and simulation (ABMS) a branch of Artificial Intelligence with an increasing use in social simulation since the debut of the XXI century to deal with complex domains (Gilbert, 2004).

This thesis follows the first approach, using Serious Games as a method for data collection, and traditional questionnaires for validation and calibration.

1.4.1 Method

A framework to capture the complex and uncertain activities of pedestrians in the real world was devised as a first class abstraction for behaviour elicitation by (Rossetti et al., 2013), and coined **SPEED**, an acronym for **Simulation of Pedestrians and Elicitation of their Emergent Dynamics**. The fundamentals of the SPEED framework are described further in Chapter 4.

The methodological approach followed to implement an instantiation of the SPEED framework can be summarized to the following steps:

i) To design a set of scenarios that are typically present in building evacuations;
ii) To specify the requirements of the SG and implement a prototype;
iii) To align the type of questions in the questionnaire study with scenarios in SG prototype;
iv) To carry out Expert Panel validation (based on the Delphi method);
v) To carry out a pilot study for co-validation of the questionnaire and the SG using statistical tests as well as experts on the field;
vi) To carry out data collection to further drive the artificial agents trying to recreate the players' decisions, based on their previous selections and the selected category of behaviour;
vii) To implement an agent-based simulation using the multi-agent paradigm in which each single artificial agent is modelled by the data previously collected, a process known as peer-design agents (PDA).

Every step previously enunciated consists of the research path leading forward to the validation of the hypothesis stated in Sub-section 1.4.3 is discussed further in Chapter 4.

1.4.2 Research Questions

Having previously identified, in the problem statement section, the need for elicitation methods and behaviour modelling techniques, that are traditionally (1) done by direct observation or by means of questionnaires; and (2) existing evacuation simulators (and pedestrian simulators in general) still lack data on human behaviour for allowing better modelling of the evacuees in emergency situations.

Consequently, some research questions (RQ) were identified:

RQ1. To which extent are responses to questionnaires related to the actual behaviour of the subjects while playing the game?

RQ2. To which extent can SGs be used as a behaviour elicitation tool?

RQ3. How can data collected through SGs be effectively used to breed and grow artificial societies in agent-based crowd simulators?

These questions make-up the starting point for this PhD research and the ground upon which research method towards the Conceptualisation and validation of the proposed solution will be devised.

1.4.3 Hypothesis

Based on the need of new elicitation methods for human behaviour and the use of the collected data to improve evacuation models (and pedestrian simulators in general), the hypothesis formulated are the following:

H1. SGs are a valid means for data collection of human behaviour, complementary to questionnaires;

H2. SGs are a valid means for behaviour elicitation;

H3. Data collected through SGs can be used to breed and grow artificial societies in agent-based simulators, leveraging the implementation of the PDA concept.

The goal of the first hypothesis is to prove that SGs are a valid and complementary means to collect data with respect to the more traditional way using stated preferences questionnaires.

Moreover, the second hypothesis goes further by stating that SGs are a valid means for behaviour elicitation.

And, at last, that this data and elicited knowledge can be used by agent-based simulators using intelligent agents mimicking humans, and as such, requiring truly human behaviour features.

1.4.4 Expected Contributions

The expected results driving the goals of this research are the following:

1. A methodology for co-validation of questionnaire-based studies using SGs techniques;
2. A low cost tool to support behaviour elicitation;
3. A means for acquiring more realistic behavioural data to feed models of artificial societies towards the implementation of the SPEED framework using the PDA concept.

The conceptualisation of the SPEED methodology is the scientific contribution. Albeit the SPEED project is a wider methodological framework beyond the scope of this PhD thesis, it very well represents the great potential for generating further research having this thesis as a starting point.

As for the applicational point of view, this thesis main contribution consists in using SGs as a complementary low cost tool for the traditional questionnaires. The virtual environment based on the concept of Serious Games, might be used as a training tool to replace, if not totally at least in part and complementarily, real-world fire drills, representing a cheaper and more practical alternative to expensive and infrastructure-dependent traditional approaches.

From the technological perspective, the ability to serve as an aid to support behaviour elicitation by inferring behaviour patterns from player’s logs during the games. The SG can be enriched with more scenarios to be conceived and added to the SPEED framework, building upon the experiments implemented and described in the present thesis.

1.5 Document Structure

This thesis has a structure of seven chapters (as depicted in Figure 1.1). Each chapter starts with a small description of its content and ends summarizing the contribution thereof in the thesis, introducing the reader to what follows in the following chapters.

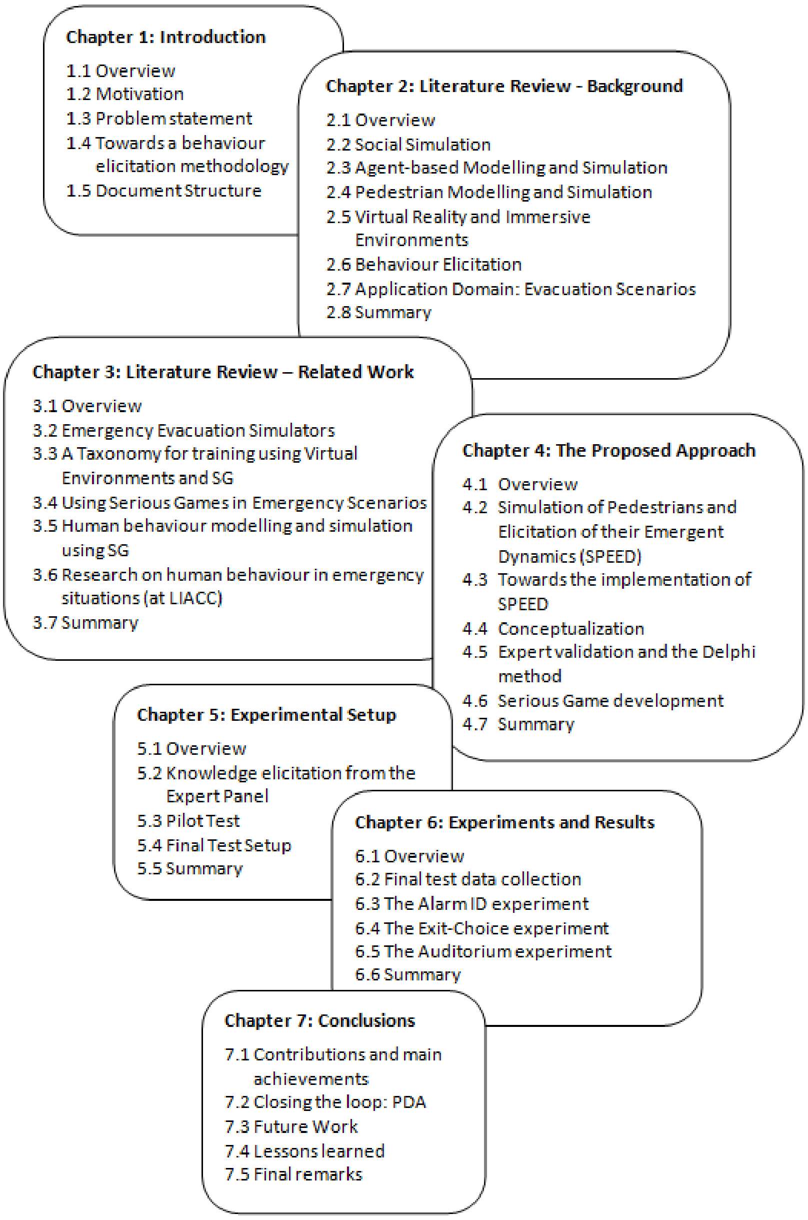


Figure 1.1 – Document structure overview

In Chapter 2, a literature review focusing on the background of the domains related to the areas of research are presented: namely Social Simulation, Agent-based Modelling and Simulation, Pedestrian Modelling and Simulation, Virtual Reality and Immersive Environments, Behaviour Elicitation and finally some concepts regarding the application domain, such as Evacuation Scenarios.

Chapter 3 describes some related work based on a literature review including an overview of Emergency Evacuation Simulators, a taxonomy for training using Virtual Environments and SGs,

SGs applications within Emergency Scenarios, use of SGs for human behaviour modelling and simulation. This chapter ends presenting the Portuguese research on Human Behaviour in emergency situations.

In Chapter 4 the proposed methodological approach is presented with the Conceptualisation experiment designs and their corroboration by the international expert panel using the Delphi process. This is followed by the description of some preliminary experiments towards the implementation of serious games.

Chapter 5 presents the experimental setup, with the help from the expert panel and using the Delphi method, as well as the pilot tests carried out, together with preliminary results and respective analysis.

Detailed discussions on the revised experiments and final results are presented in Chapter 6.

Finally, Chapter 7 draws conclusions, especially focusing on how the expected contributions were met, and presents a critical overview of the results obtained in this thesis, identifying main lessons learned and opportunities for future research stemming from the mains contributions of this work.

2. Literature Review: Background

2.1 Overview

This chapter comprises the literature review summarizing some key concepts and the fields of research that are related to this thesis. It begins by introducing the Social Simulation concept, and its relation to Artificial Intelligence within the context of human behaviour and participatory simulation aimed at designing intelligent agents. Agent-based modelling and simulation are then presented, including the concepts of intelligent agent, multi-agent systems and some applications including pedestrian simulation.

This is followed by an introduction to pedestrian modelling and simulation emphasising on all aspects that are related therewith, such as crowd behaviour, individual and crowd behaviour in emergency situations including panic. Crowd phenomena are explained: herding or flocking, arching, clogging and stampede. Then, some pedestrian modelling techniques are listed, namely the cellular automata, space behavioural models, magnetic and social forces models. This section concludes with some studies concerning human behaviour in fire situations, simulation techniques, and applications of pedestrian simulation. Virtual reality and immersive environments are explained, including CAVEs, Videogames, and virtual worlds, Serious Games, and the concept of gamification, which has gradually become the basis of so many mainstream applications.

The following section exposes the need for human behaviour knowledge and the methodologies used for eliciting it, including the contributions of Artificial Intelligence and the Serious Games concept in the context of fire safety and egress analysis. The chapter concludes by presenting the application domain, fire safety and fire risk analysis, some legislation issues, focusing on the topics such as safety of building occupants and how to accomplish it, typically by fire drills.

2.2 Social Simulation

2.2.1 Social Sciences and Simulation

Social simulation is a rather recent research field in which behavioural methods are applied to the social sciences. Models are created by social scientists to perform experiments on scenarios and what-if simulations that would be very complex if not impossible to undertake without the help of digital models in computers. According to Nigel Gilbert, a possible definition of social simulation resides in "the construction of computer programs that simulate aspects of social behaviour and can contribute to the understanding of social processes." (Gilbert, 2004)

The same author states that social science research can either: i) develop some kind of theory or model in textual form; ii) represent such theories as an equation; iii) or express theories as computer programs thus allowing social processes to be simulated on a computer.

For Axelrod (2003), simulation "is a third way of doing science in contrast to both induction and deduction." This author proposes the use of simulation as an effective tool for discovering consequences of simple assumptions, and as a result fostering research in social sciences (Axelrod, 2003).

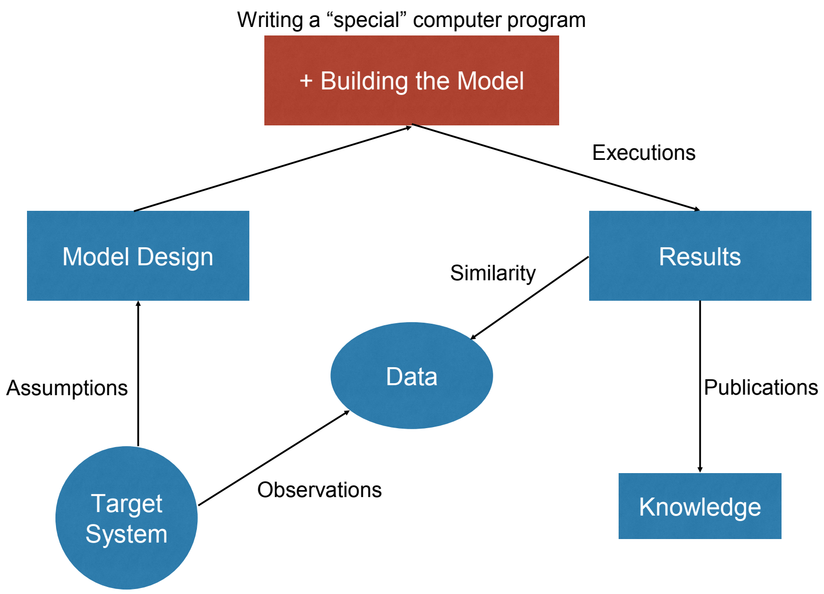


Figure 2.1 – Methodological approach for creating a computer simulation (Drogoulet al., 2003)

Computer simulation consists in building a model of an actual or theoretical system on a digital computer, using some data and performing some calculations, by means of "special"[1] programs, to produce numerical outputs for further analysis (Drogoul et al., 2003). The model design involves writing some sort of computer code, based on assumptions of a target system. Using data from knowledge acquired by observations, physical laws, experts or literature, one or more executions are performed, the simulation phase, producing some sort of output that will be compared with the target system (as depicted in Figure 2.1).

[1] Authors emphasize on the "special" program, meaning that the code resulting from an algorithm must somehow translate the model into something usable on a computer.

2.2.2 Artificial Intelligence for Human Behaviour Simulation

Artificial Intelligence (AI) is the branch of computer science that aims to replicate the human cognitive processes using computers or other machines, such as robots. John McCarthy, who coined the term in 1955 defines it as "*the science and engineering of making intelligent machines*" (McCarthy et al., 2006).

AI techniques have been widely used in different applications, from mimicking human behaviour in robots and other physical devices to simulating reasoning and decision-making abilities within systems intended to be rather autonomous. Also, Distributed AI (or DAI, for short) is a subfield of increasing interest in which problems are tackled on a distributed basis, allowing for smaller pieces to be modelled in detail whereas the system performance emerges as a result from the combination of them all. This sort of structure very much resembles a society of several interacting entities and has inspired some research in the Social Sciences, for instance (Cordeiro et al., 2011b).

The problem of understanding the emotional context towards the creation of a model that incorporates emotions and the behavioural aspects of humans in the decision making process leads to the concept of Emotional Elicitation (Sarmento, 2004). This aspect is of paramount importance when we are trying to envisage a framework composed of intelligent agents mixed in a certain environment where the individual and collective behaviour has sometimes conflicting goals and approaches to achieve them. To model such agents, the knowledge on the mechanisms underlined and insights into their inner aspects that will ultimately influence their behaviour must be available and be trustworthy. Humans are much affected by emotions and emotional states, and these are intimately related to the surroundings that will somehow interfere in the decision-making processes that are so unpredictable.

2.2.3 Participatory Simulation

According to (Drogoul et al., 2003), one of the most difficult tasks when designing a model is the formalization of the agents' behaviours. This step sometimes requires several iterations for the extraction or elicitation of important knowledge on how different behaviours evolve. One possible approach is by performing participatory simulations, by allowing experts and non-experts to interactively define the expected behaviours through role-playing games (RPG) or by being immersed as "human agents" in the loop of running simulations.

This technique can be used as a complement to knowledge engineering, for eliciting and organizing knowledge of experts on agent behaviours (Macal and North, 2005).

2.3 Agent-Based Modelling and Simulation

2.3.1 Intelligent and Autonomous Agents

One possible definition of an agent is: "*an autonomous entity, capable of perceiving the surrounding environment through a set of specific sensors and of acting upon the same environment, maybe directly affecting its current state, through reasoning specific effectors. They feature a set of decision-making mechanisms underlying their abilities and may exhibit communication channels allowing them to interact with each other* " (Russell and Norvig, 2010). Basically, agents are elements capable of individually deciding upon their actions according to their own perceptions and interactions (Ribeiro et al., 2012a).

Agents are expected to have certain capabilities that enable them to be called "intelligent", such as: reactivity, proactiveness, social ability. They should be able to perceive, reason, react, memorise, and take initiatives based on their knowledge, past experience, pre-defined rules, or according to the modeller's specification (Wooldridge, 2002). In this definition, proactiveness refers to the ability of agents to perform some actions on their own initiative. Agents can interact and communicate with other agents, make decisions on their own, and react to external stimuli. In contrast, entities in a discrete-event simulation model are rather simple, reactive, and limited in capabilities. Entities in most discrete-event simulations rely on some central mechanism, e.g., the event scheduling function to invoke actions to change entity states, and entities have no learning or cognitive reasoning. For example, consider a queuing simulation model in which the entities in a queue determine whether to stay or leave by communicating and gathering waiting time information from nearby entities.

2.3.2 Multi-Agent Systems

Multi-Agent Systems (MAS) are a subfield of DAI whose abstraction approach, motivated by society paradigm, basically consists in representing the application domain by means of multiple autonomous entities, called agents. This paradigm emerged in the 1980's, but was only in the middle of 1990's when it began to be largely studied. A distributed perspective was adopted by scientists, which can be seen as a computational system composed by various entities capable of mutual and environment interaction (Wooldridge, 2002). Arguably, the practical application of MAS-based models is still questionable. It is reasonably consensual that much work is still needed so that one can figure out the rules that predict crowd behaviour, both in normal and in emergency scenarios. Indeed, MAS still lacks adequate means for eliciting social interactions to model more realistic scenarios building upon multiple individuals interacting. One of the main issues arising in this context, therefore, is how to capture the behavioural characteristics of subjects, especially under stress, in crowded environments. On the other hand, influencing behavioural patterns towards socially efficient systems is another goal to pursue in this area (Cordeiro et al., 2011b).

In recent years MAS has been used as the preferred method to simulate crowd movement in different scenarios (Cherif and Djedi, 2006; Ji and Gao, 2007; Murakami et al., 2002; Pan et al., 2007). The complexity of agent modelling, the need for data and rules to feed the system and the computational time needed (although according to Moore's Law computers' processing power keeps increasing at a fast pace) have created some difficulties to this approach (Almeida et al., 2011). However, investigation is going on and papers describing work in this field are becoming more common (Jafari et al., 2003; Kin et al., 2010; Zoumpoulaki et al., 2010). The possibilities offered by MAS are vast, as long as social rules and interaction knowledge among people is known and fed to the model (Sharma, 2009).

2.3.3 The Conceptualisation of Agent-Based Modelling and Simulation

Agent-Based Modelling and Simulation (ABMS) is under the umbrella of DAI, for which the main modelling metaphor is the so-called intelligent agent. When multiple agents are put together, they can perform rather socially, building upon MAS, which makes ABMS ideal to represent many scenarios of our daily lives (Cordeiro et al., 2011a; Rossetti et al., 2013).

Bonabeau states that ABMS is a mindset more than a technology in which the modelling paradigm is based on a microscopic approach rather than a macroscopic modelling perspective. Yet, the apparent simplicity of this concept becomes rather complex, when it comes to the implementation of agents in practical applications (Bonabeau, 2002). A survey of Agent-Based Modelling (ABM) practices, based on a period of time from 1998 to 2008, refers to different fields of application such as complexity, chaos, cybernetics, and cellular automata. However, due to the complexity and difficulty of analysis, ABM systems not always produce meaningful results (Heath et al., 2009).

Bearing in mind the aforementioned characteristics, it is easy to understand why ABMS has gained a strong emphasis as a key instrument to model and simulate different social phenomena. Social simulation with ABMS has emerged as a research field where computational methods are applied to Social Sciences with connections to MAS. This kind of approach is particularly adequate for representing social relations on the basis of behavioural models exploiting the emergent behaviour of the system. For these reasons, ABMS has been widely used to simulate pedestrian interactions and crowds in a vast range of different scenarios, naturally including evacuations and risk situations.

Agent-based simulation (ABS), as it also regarded, can in summary be considered as particular genre of simulation using the concept of autonomous intelligent agents that interact somehow with each other. A possible definition for ABS is "a hybrid discrete-continuous simulation model with proactive, autonomous, and intelligent entities" (Kin et al., 2010). According to the same authors, "*while the precise definition of ABS varies across fields (or even in the same field), the philosophy and usages of ABS are similar: simulating interactions of autonomous objects (called agents) to identify, explain, generate, and design emergent behaviours.*"

Agent-based models are a good metaphor for representing social interactions and behaviour, which is of paramount importance in crowd modelling and simulation (Ribeiro et al., 2012a).

2.3.4 Applications

Some authors (Epstein, 1999; Kin et al., 2010; Macal and North, 2007, 2005; Wooldridge et al., 1999) have promoted in the past years the advantages and benefits of using Agent-Based techniques for modelling and simulation compared to more traditional approaches, in particular when applied to social sciences. Popular fields of study where the agent-based paradigm is used for modelling and simulation include economics, social sciences and biology (Heath et al., 2009).

When it comes to modelling the behaviour of a crowd, the ABMS is the best approach to tackle this problem, considering that a crowd is a particles system in which each individual has its own agenda, besides their physical characteristics such as age, gender and physical aptitude. Even the psychological state differs from person to person (Aguiar et al., 2010).

In the field of evacuation, there are various examples in the literature using ABMS or MAS, as the underlying metaphor for the architecture of the systems built (Drogoul et al., 2003; Hajibabai et al., 2007; Pan et al., 2007).

2.4 Pedestrian Modelling and Simulation

2.4.1 Scope and Applications

Pedestrian Behaviour Simulation has gained a great interest, both from the scientific community as well as from practitioners and the industry, as an important area of research and activity. Applications range from computer games to more serious usage like traffic prediction, and simulation of evacuation scenarios both inside buildings and outside. Indeed, evacuation plans and other kind of analysis in crowded environments are especially important. Some examples that foster such a tendency include the concern designers now start to demonstrate while projecting the next generation of complex buildings for smarter cities.

City planning and urban design is another possible application for pedestrian simulation. For engineers and architects, the safety issue is crucial, not only in fire situations but also to prevent stampede and overcrowded disasters, for which many examples are well known (Averill and Mileti, 2005). Modern architecture buildings, like skyscrapers, with large occupancy and multiple floors, or stadiums need tools to validate if they are compliant with fire safety regulations. Evacuation simulators are increasingly used for this purpose (Almeida et al., 2011; Kuligowski et al., 2010; Santos and Aguirre, 2004; Timmermans, 2009).

But there are other fields requiring the need of artificial societies and synthetic populations. For instance, some public transportation vehicles such as trains, planes, and ships, are nowadays designed bearing in mind the safety issues, using specifically developed simulators, e.g. maritimeExodus (Deere et al., 2009), airExodus (Gwynne et al., 2005).

In a less dramatic context, the dynamics of pedestrians moving around in cities using the streets and intermodal interfaces is another application for which the models of human interactions are needed (Al-nasur and Kachroo, 2006; Liu and Pan, 2003). The integration of pedestrians when travelling in transportation systems requires proper simulation techniques (Liu, Pai, Chang, & Hsieh, 2001). Many models exist for traffic simulations where the interactions between various vehicles coexisting in the same network are simulated. The pedestrians are an important aspect to consider in such simulations. The correct modelling of their behaviour and movement is fundamental as well as the interaction with vehicles, particularly when they are autonomous, for collision avoidance (Premebida et al., 2007). Furthermore, the management of pedestrian flows demands understanding both the collective pedestrian flows as well as the individual pedestrian movements in the flow (Hoogendoorn and Bovy, 2004).

2.4.2 Crowds Behaviour

Crowds have been empirically studied for the past decades (Coelho, 1997; Cordeiro et al., 2011a; Fruin, 1993; Pauls, 1995). In their common environment pedestrians tend to show some basic attributes. For example people always try to find the shortest and easiest way to reach their destination. If possible they avoid detours, even if the shortest way is crowded. The basic principle is the "least effort principle", which means everyone tries to reach their goal as fast as possible spending the least amount of energy and time (Almeida et al., 2011).

When walking along a sidewalk, in case of head-on encounters, a binary decision takes place: pedestrians need to choose whether to evade the other person on the right-hand or on the left-hand side. This decision process goes along with a significant decrease of walking speed (Moussaïd et al., 2009). This is an example of the interaction processes that happen between pedestrians walking at normal pace.

Helbing et al. (Helbing, Molnár, Farkas, & Bolay, 2001) have studied pedestrian movement by the analysis of video films and direct observations. They found out that the apparently chaotic or random pedestrian behaviour has some regularity, such as:

a) Pedestrians avoid detours or moving opposite to the desired walking direction;
b) The selected walking speed corresponds to the most comfortable (least energy-consuming) in a trade-off between need (urgency to reach a certain goal in a given time) and effort;
c) There is a certain distance among individuals and obstacles that varies with their hurry, density and acquaintance (forming groups);
d) The behavioural strategy is more or less automatic, meaning that they do not think continuously of their path or way-finding but act as an experienced car driver does.

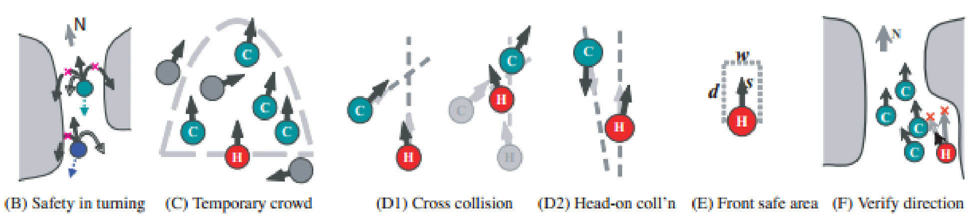


Figure 2.2 – Pedestrian reactive behaviours (Shao and Terzopoulous, 2007)

Another approach to model pedestrians in urban environments (Shao and Terzopoulos, 2007) has identified a set of reactive behaviour rules (see Figure 2.2). The pedestrians' movement depends on goals (at strategic level), the path selection (at a tactical level) and speed, direction and obstacle avoidance (at a lower level). The decision-making process is done combining such three hierarchical levels.

Despite all knowledge regarding pedestrian movement, there are still some unknown issues about the normal pedestrian behaviour. The variables that might affect their movement are many and hardly quantifiable, justifying the need for further research in this domain.

2.4.3 Individual and Crowd Behaviour in Emergency and Panic Situations

Most of the normal behaviour vanishes when pedestrians face an emergency situation. Similar effects can be observed for example in crowds trying to get the best seats at a concert or consumers running for sales. Observations made for pedestrian crowds in emergency situations feature typically the same patterns. As people try to leave the building as fast as possible, the desired velocity increases which leads to some characteristic formations. The concern about the comfort zone diminishes while finding the most convenient and shortest way becomes the main priority. Such situations often happen during ingress and egress of public settings (Sime, 1995, 2001, 1985, 1980). Sime (1995) proposes the integration of crowd psychology and engineering; whilst the latter has more emphasis on the physical environment and places the focus on subjects as static and dynamic objects, psychology is rather concerned with the perspective of crowd members that think and behave.

A common phenomenon is people running for the exit they used as an entrance, even though other exits might be easier to reach or even allow safer egression (Helbing et al., 2002). According to (Pan et al., 2007): "*...most people tend to exit a building following the route with which they are most familiar and ignore alternative routes. Decision making is usually straightforward and quick.*" This behaviour is many times not the safest option since emergency exits tend to be neglected and people use longer and perhaps more dangerous routes.

Individuals and crowd also might lose the ability to orient themselves in their surrounding and thus show herding or flocking behaviour (Reynolds, 1987). Not only do they lose certain abilities, but they also start to exhibit new behaviours like pushing or other physical interactions.

Crowd crushes may lead to panic. However, the definition of panic is not consensual among researchers (Ma and Larrañaga, 2011; Mawson, 2005; Rogsch et al., 2008). Sime (1995) states that words 'panic' and 'crowd' have a negative connotation; typically used by media commentators reinforcing assumptions made about people's behaviour with implicit or explicit notions of hysteria or unruly mob (Sime, 1995). At the Pedestrian and Evacuation Dynamics (PED) conference in 2008, 16 different definitions of panic were compiled (Klingsch et al., 2010). Whilst some state that panic is a myth (Fahy et al., 2012; Rogsch et al., 2008) others say that there are some misconceptions regarding the definition of panic (Helbing and Mukerji, 2012).

França et al. (2009) proposed a conceptual model for panic using Multi-Agent Systems (MAS) theory to simulate an artificial world able to transpose from a crowd in panic behaviour to a similar conceptual model. Their idea is to use the conceived tool for modelling and understanding the complex phenomena arising in crowds such as coordination, formation of coalitions and groups, conventions and norms, micro to macro linking (França et al., 2009).

Cordeiro (2011a) presented a case-study on the human behaviour under fire situations, applied to the Portuguese population nationwide. According to survey carried out, 93.33% of respondents consider that in a fire situation there will be panic (Cordeiro et al., 2011a). These results collide with the observations of other researchers who consider that in emergency situations panic did not occur (Fahy et al., 2012; Sime, 1980). One explanation may be due to the fact that “stampede” has no direct translation to Portuguese. And people might have a different concept of panic, relating this phenomenon with the uncontrolled movement of crowd during an unpredictable event, such as an emergency situation.

The importance of the panic concept, whatever definition is used, and the phenomena related to crowds, cannot be ignored and has thrived much research that is still ongoing (Lawson, 2011; Ma and Larrañaga, 2011; Shiwakoti and Sarvi, 2013).

2.4.4 Herding or Flocking

Herding or flocking occurs when a large group of people are together, sharing a common bond; for instance when trying to leave a crowded space in emergency situations (Figure 2.3 a).

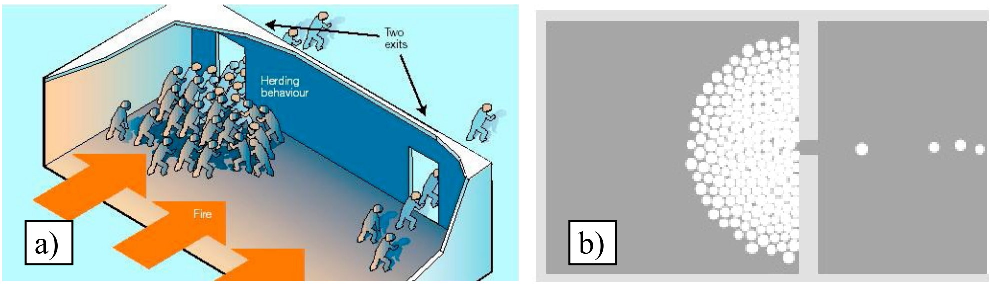


Figure 2.3 – a) Herding behaviour of a crowd when trying to escape from smoke-filled room; b) Arching and clogging (Helbing et al., 2001)

When people get nervous and feel panic, they lose the ability to act logically and to decide on their own. As a result of this lack of independence, people tend to follow others in the assumption they could get them out of the dangerous area. On one side this could actually help people to escape faster. But, if smoke is reducing the visibility or the person leading the group does not know the layout of the building well enough, this might reduce the chance of finding an exit. So instead of people wandering around on their own, flocks of people start to form with increasing anxiety or nervousness.

2.4.5 Arching, Clogging and Stampede

Observations have shown a phenomenon called arching (Helbing et al., 2002, 2000; Schadschneider et al., 2009), which appears when a big crowd with a high desired velocity tries to pass through a door. Instead of passing through the door in less time, or giving the oncoming pedestrians a chance to pass through the door, the door gets clogged and the crowd forms an arch-shaped configuration (Figure 2.3b). This phenomenon leads to blockage of the exits, diminishing the evacuation speed, until the exit clogs leaving the people trapped.

(a) (b)

Figure 2.4 - Arching and clogging: a) The Station nightclub fire, USA, 2003; b) Stampede in Halloween party, Madrid, Spain, 2012 (J.F.M. Silva et al., 2013)

One example that was deeply studied was "The Station" nightclub fire on 20th February 2003, killing one hundred people (Grosshandler et al., 2005) where many occupants were trapped at the main door in front of the building. One survivor reports that he tried to pull one man and then one woman; both trapped at the bottom of the pile of people and could not get them to move the tiniest bit. At the time of the event, a film crew from a TV station was running a documentary about the concert going on. When the fire started, the cameraman kept filming thus providing an invaluable documentation of the events. The unedited full image footing of the Rhode Island “The Station” fire was released almost ten years later on the YouTube website[2] (Fig.2.4a).

The Love Parade concert in Duisburg, Germany, on July 24, 2010, ended dramatically with 21 people killed and over 500 injured. A research conducted by Helbing & Mukerji, identified some misconceptions, concerning the concepts of ‘mass panic’, ‘stampede’, ‘crushing’ and ‘trampling’. These events were caused by high density and body contact, the absence of communicated reasons for the delays and threatening high-density conditions. When trying to avoid the so-called ‘domino effect’ people may be forced to step on others, and fall due to turbulent waves in the crowd (Helbing and Mukerji, 2012).

During the 2012 Halloween party, in Madrid, Spain[3], for unknown reasons, presumably due to overcrowding and the rush of youngsters trying to move to the concert hall to watch the performance of a famous artist, people started to crush into one of the access tunnels. Five young women died crushed by the crowd (Fig.2.4b).

Another tragic event, was the fire at the Brazilian discotheque “Kiss” where 242 young lives were lost, due to overcrowding and only one exit (January 27th, 2013). The lack of education in fire safety of security personnel was also pointed out as one of the causes for accounting so many victims (Almeida et al., 2014c).

In Portugal, the most deadly occurrence of stampede and clogging of exits was the fire of the Baquet Theatre in Porto, on March 21st, 1888, where over 120 people died (Filinto, 1888). The theatre was full, with over 600 people (including public, orchestra and performers) when the fire erupted. The exiguity of the exits in addition to panic led to the tragedy.

2.4.6 Pedestrian Modelling

Although some attempts of modelling and simulating pedestrian movement have been around for decades, this field of research recently received a clear boost in attention in a variety of disciplines, not only in the ones traditionally concerned with pedestrians such as transportation, urban planning and design, but also in applied physics, computer science and artificial intelligence. In the latter, pedestrian movement is often viewed as an interesting case to show properties of complexity theory and multi-agent models such as aggregate patterns emerging from simple principles applied to microscopic agents (Timmermans, 2009).

[2] http://www.youtube.com/watch?v=Jae1fglq-9g
[3] http://edition.cnn.com/2012/11/01/world/europe/spain-halloween-stampede/index.html

The more common representation models (see Figure 2.5) use one of the three following formats (Castle, 2007):

- Coarse Network (or physics-based models of particle flow) typical of macroscopic models;
- Lattice or Cellular Automata;
- Continuous space.

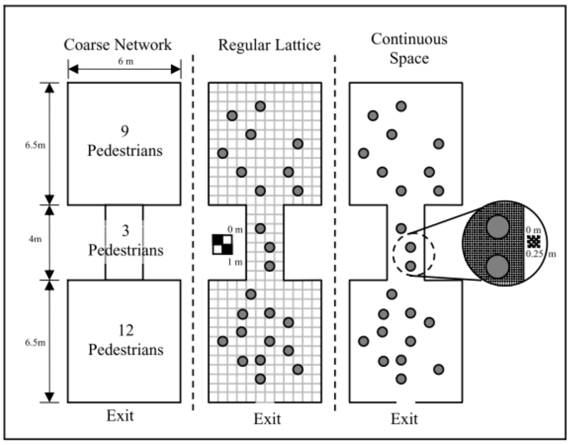


Figure 2.5 - Illustration of the three more common representation models (Castle, 2007)

Flow-based or coarse models use the analogy with fluid and particle motion. The basic principle is the density of nodes in continuous flows. These are called macroscopic models. Characteristics are defined beforehand thus all particles behave in the same way without any particularization of individuals. In this kind of models the simulated physical environment is defined as a network of nodes. The nodes represent physical structures, such as rooms, stairs, lobbies, and hallways that are all connected and comprise a single structure from which an evacuation is executed. The nodes contain people. Certain nodes are designated as destination nodes identifying the possible exits. Besides nodes, the model also requires the provision of specification for arcs. Arcs are passageways between building components with two variables: traversal time or the amount of time it takes to cross the passageway, and an arc flow capacity which delimits the amount of human occupants that can cross the passageway per unit time. One example of this type of modelling is EVACNET4 (Santos & Aguirre, 2004; Kisko, Francis & Nobel, 1998).

Some authors call these models as “coarse models”. They are useful to simplify and minimize the number of constituent parts of the graph, thus reducing modelling time, improving performance and even results analysis (Castle, 2007).

In **Cellular Automata** (see Figure 2.6) models space is organized in a matrix with a two-dimensional array. The simulation technique uses a time-frame pre-defined in which the occupants can move from one position or node to another, assuming it is free or it is not an obstacle. Each element can have several values: empty, occupied by a person, occupied by some object, or part of the limits (wall). The movement occurs at every step of the defined time-frame when occupants can move to one of the adjacent nodes.

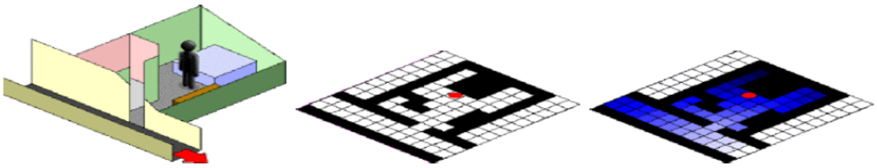


Figure 2.6 - Cellular Automata (Jafari et al., 2003)

Microscopic and macroscopic analyses are both permitted. This type of model is simple to implement but fails when trying to replicate the erratic movement of people in real life, since only limited movement is allowed. Also it is not easy to model different speeds and interaction between people, due to the grid shape of space. Nevertheless this is the most used type for crowd modelling in games and more serious applications. One popular example is Exodus in early versions (Pan, Han, Dauber & Law, 2007). Another example is EGRESS (Santos and Aguirre, 2004).

The Multi-Agent Systems (MAS) approach to this problem uses a microscopic approach because it allows to model each individual person with their own unique characteristics, although keeping the interactions emerging from the surrounding persons. SIMULEX is referred to as being the first application to use MAS (Santos and Aguirre, 2004). Exodus' latest versions and PedGO also use MAS (Jafari, Bakhadyrov & Maher, 2003). In MAS simulators each agent is modelled independently thus permitting a more realistic approach to the real life scenarios (Wooldridge, 2002).

The most advanced agent-based simulators use intelligent architectures, where actions are driven by utility functions, or BDI (Beliefs, Desires and Intentions) architectures (Liu et al., 2013; Rossetti and Liu, 2005; Rossetti et al., 2002b). These models aim to replicate the reasoning process used by humans which is mainly based on measuring the benefits that each action or decision might have (Wooldridge, Jennings & Kinny, 1999). In the BDI model agents are driven by Desires (the goals) according to certain Beliefs (set of knowledge of the world) and Intentions (actions) to fulfil the Desires (Rossetti et al., 2002a). For instance, in an emergency evacuation simulation, agents' Desires are to leave the place where they are, due to fire or other hazard, as quickly as possible, using the fastest and safest path (following the Beliefs) and taking the necessary actions (Intentions) (Almeida et al., 2011; Rossetti, 2002).

Spatial behavioural or continuous models, instead of a discrete space model (e.g. cellular automata) use a continuous 2D plane, allowing the occupants to walk from one point in space to another throughout the building (Kuligowski, Peacock & Hoskins, 2010). These models have the ability to simulate the presence of obstacles and barriers in building spaces that influence individual path route choice, allowing movement in any direction, whereas cellular automata only has 4 directions or a maximum of 8 if diagonals are considered. Path planning has more possibilities and routes can be more realistic. But it is also more complex to control the agents' movement since they are not tied to individual cells. Pan et al. propose a framework MASSEgress where humans are represented by computational agents with visual sensors (Figure 2.7) that analyse the surrounding environment (Pan et al., 2007).

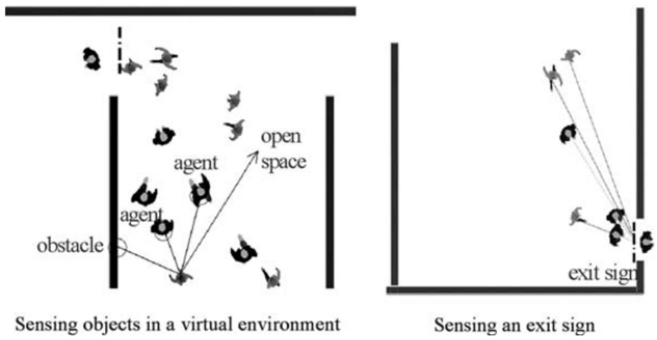


Figure 2.7 -Visual sensors using the ray tracing method (Pan et al., 2007)

In this model, following a bottom-up approach, by organizing the agent decision process into a hierarchical structure, Pan et al. propose a three level hierarchy, shown in the Figure 2.8:

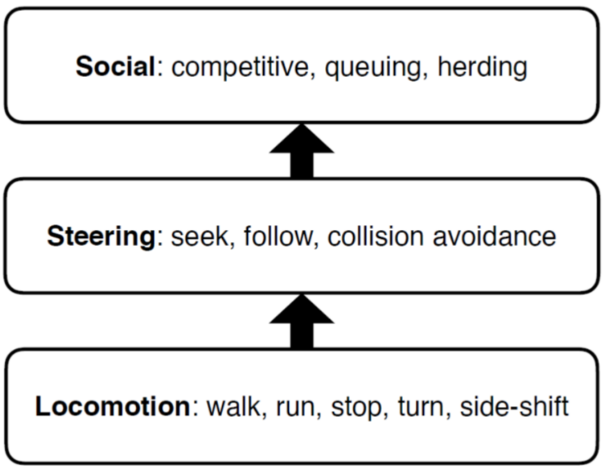


Figure 2.8 -A hierarchy of agent behaviour (adapted from Pan et al., 2007)

In the lower level are the basic motion functions such as: walk, run, stop, turn or side-shift. These functions are the building blocks of the agent movement. The middle level has the steering functions, when the agent decides in which direction they should move, and also taking into account the collision avoidance. The upper layer has the high level behaviour decision process, regarding the strategic decisions that the agent will take.

2.4.7 Magnetic Forces Model and Social Forces Model

Two of the various possible ways to model the pedestrian movement and interactions between persons, obstacles and the environment, are the Magnetic Forces Model (Okazaki and Matsushita, 1993) and the Social Forces Model (Helbing and Molnar, 1995).

The Magnetic Forces Model uses as a metaphor the magnetic field and the relations of attraction and repulsion among pedestrians and the surrounding environment. In this model, the movement of each pedestrian is simulated by the motion of a magnetized object in a magnetic field which exerts attractive force on the different kind of magnetic poles and which exerts repulsive force on the same kind of magnetic poles. Positive magnetic pole is given to each pedestrian and obstacles like walls and columns. Negative magnetic pole is located at the goal of pedestrians. Each pedestrian movement towards his goal is induced by the attractive force caused by the negative magnetic pole at his goal, avoiding collisions with other pedestrians and obstacles by repulsive forces caused by the positive magnetic poles.

The motion of pedestrians using the Social Forces Model is based on a similar concept, where the motion is related with the internal motivations of individuals rather than magnetic ones. This approach is referred widely in the literature as one of the models used by pedestrian and evacuation simulators (Crooks et al., 2010; Korhonen et al., 2010; Pelechano and Malkawi, 2007).

2.4.8 Human Behaviour in Fire Situations

Most of the focus of evacuation models is on determining and predicting the evacuation phase, i.e., how long it takes an occupant to move from their initial position to outside of the building, ignoring the pre-evacuation time. This time is related to the pre-movement, that is, the prediction of behaviours that occupants perform before the evacuation that can delay their safety (e.g., searching for information, fighting the fire, and helping others). Instead of modelling and predicting behaviour of simulated occupants, evacuation models often make assumptions and simplifications about occupant behaviour, assuming that they will move directly to an exit following the shortest path. This approach is unrealistic and likely to produce inaccurate results.

When studying the evacuation process, Kuligowski recognized four phases shown in Figure 2.9 (Kuligowski, 2008). Each phase can be described as follows:

- Phase 1: perceiving external physical and social cues from the environment;
- Phase 2: interpretation of the cues received;
- Phase 3: decision-making process;
- Phase 4: actions based on the previous phases; if new information/cues arise, the process will restart.

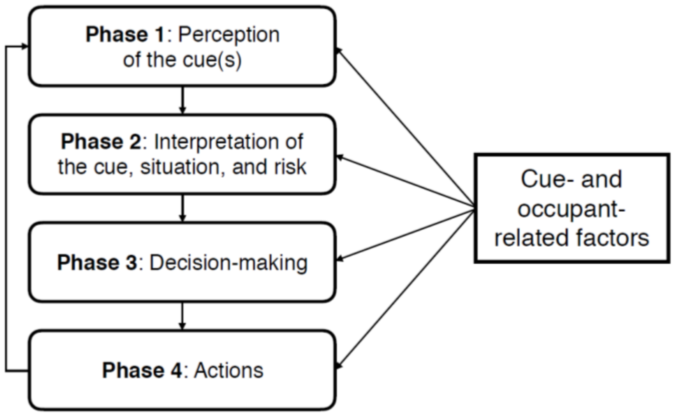


Figure 2.9 - A conceptual model of the behavioural process for building fires (Kuligowski, 2008)

Kuligowski identified three interpretation stages: interpreting the cues received, interpreting the situation (i.e. as a fire), and interpreting or assessing the risk to the self and/or others (Figure 2.10).

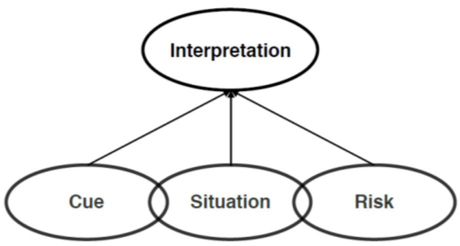


Figure 2.10 - Phase involves interpreting the cue, the situation, and the risk (Kuligowski, 2008)

Most evacuation models emphasise on the occupant’s progress, obstacles avoidance, and kinematic issues, as opposed to reasoning on cues interpretation. Typically, when the evacuation process starts, the occupant’s movement is towards safe places. Some models might add a delay before the evacuation process begins. In Kuligowski model all cues are continuously perceived, evaluated and decisions are made with respect to the input received and the reasoning process.

Occupants' behaviour is the result of a reasoning process. Each process begins with new cues and information from the physical and social environment. First, cues need to be perceived, then they are interpreted, and then a decision is made so as to what action (including inaction) to be undertaken. Some influential factors for the perception phase and a subset of the interpretation phase of the behavioural process are listed in Table 2.1.

Table 2.1 – An overview of influential factors for Phases 1 and 2 of the behavioural process (Kuligowski, 2010)

Factors	Phase 1	Phase 2: Interpretation	
	Perception	2a: Definition of the Situation as a Fire	2b: Definition of the Risk to Self/Others
Occupant-based pre-event factors			
Has experience with fires (Yes)	Increases	Increases	Increases
Has knowledge of fire/training (Yes)	Increases	Increases	Increases
Habituation with environment (Yes)	Decreases	---*	---
Has knowledge of routes (Yes)	---	---	Decreases
Has frequent experience with "false" alarms (Yes)	---	Decreases	---
Has a feeling of security in building (Yes)	---	Decreases	---
Has a perceptual disability (Yes)	Decreases	---	---
Age (Older adults)	Decreases	---	Increases
Gender (Woman)	Increases	---	Increases
Speaks the same language as others (Yes)	Increases	---	---
Has frequent interaction with family (Yes)	Increases	---	---
Occupant-based event factors			
Has a higher stress/anxiety level	Decreases	---	---
Perceives a time pressure (Yes)	Decreases	Decreases	Increases
Presence of others (especially loved ones) (Yes)	Decreases	---	Increases
Proximity to fire/Visual access (Yes)	Increases	---	---
Sleeping (Yes)	Decreases	---	---
A higher number of behavioral processes (>1)	---	Increases	---
Defines situation as fire (Yes)	---	N/A	Increases
Cue-based factors			
A higher number of cues	Mixed**	Increases	Increases
Consistent cues (Yes)	---	Increases	Increases
Unambiguous cues (Yes)	---	Increases	---
Social cues (others' actions) that are consistent with an understanding of a fire situation (Yes)	---	Increases	Increases
Official source (Yes)	Increases	Increases	---
Familiar source (Yes)	---	Increases	---
A higher dose of toxic gases	---	Decreases	---
Extreme/dense cues (Yes)	Decreases	---	Increases
Visual/audible cues (Yes)	Increases	---	---
Risk information (Yes)	---	Increases	---

*Areas where no research was found is marked by "---"; **Research conflicted on the direction of influence of the factor.

During an evacuation, individuals repeat this process several times as they engage in a variety of different activities. However, future research, in the form of an in-depth study of real fire events, is needed to identify the factors that influence occupants to decide to take a specific action, and the factors that influence whether that action is ultimately performed.

2.4.9 Simulation Techniques

Simulation is the imitation of the operation of a real-world process or system, state over time, representing certain key characteristics or behaviours of the selected physical or abstract system.

There are three main reasons for developing computer simulation for pedestrian behaviours: first, to test scientific theories and hypotheses; second, to test design strategies; third, to create phenomena about which to theorize (Pan et al., 2007).

The techniques to be used by the simulators will depend on the final use or aim of the simulation. Castle (Castle, 2007) has identified a set of characteristics:

- Availability and access: this criteria refers to whether the final product is or will be available to the general public, academic use, targeted to a specific niche or private use;
- Purpose / background: general purpose pedestrian simulator, in-door use only or landscape, buildings or public transportations (like trains, airplanes or ships), scientific studies or commercial evaluation, optimization of specific criteria or safety oriented;
- Nature: microscopic, macroscopic or mesoscopic analysis;
- Enclosure representation: flow-model (coarse network or physics-based model), cellular automata or lattice, and continuous space;
- Occupant enclosure perspective: this refers to the pedestrian modelling concept adopted, if the occupants perception is set globally or individually (like in Multi-Agent Systems);
- Occupant movement: kinematic issues like speed, obstacle avoidance techniques, path-finding algorithms, interaction with other pedestrians, magnetic or social-force models;
- Behavioural perspective of occupant: no behaviour, implicit behaviour, rule-based behaviour (deterministic, stochastic, mixed), Artificial Intelligence;
- Validation: against full scale simulations, video footage, fire drills, questionnaires, comparing with other simulators;
- Support: documentation, tutorials, phone or on-line support, bug reporting / fixing, additional features development.

The aforementioned criteria will define the architecture and the core of the simulator. Moreover, the techniques to be used can be selected amongst the wide range of algorithms and models already developed and known. Some are in their infancy whilst others have been widely used and proved.

2.5 Virtual Reality and Immersive Environments

2.5.1 Virtual Environments

Virtual reality (VR) refers to computer simulated environments for recreating sensory experiences such as vision, sound, touch, smell and taste, as realistic as possible, to provide an immersion feeling to subjects (Steuer, 1992). It is also known as: virtual environment (VE), artificial reality, virtual world or cyberspace (Holloway and Lastra, 1993). The senses typically used the most in VE or VR worlds are vision and hearing.

High-fidelity simulations sometimes include VR-based CAVEs, an acronym for Cave Automatic Virtual Environment. This is also a reference to the Plato's book Republic in which the philosopher discusses inferring reality from the shadows on the cave wall (Cruz-N et al., 1993). The term CAVE is typically used when a computer-generated space or environment using a fully-immersive environment is created (Shendarkar et al., 2008).

High fidelity simulations are used in many fields for training, from military to high technical and complex applications, including sports, such as Formula 1. Other applications are to train workers for industrial purposes, fire fighters or emergency responders in dangerous situations. Airplane pilots have to spend many hours in simulators training for unexpected and potentially tragic events. This type of simulation goes back to the early days of the space epic adventure when space presented many potential hazards most of them unknown and unpredictable (J. S. V. . Goncalves et al., 2014; Rossetti et al., 2013).

The applications of VR technologies for experimental psychological research on situations that might endanger the participants have gained a boost in recent years (Kinateder et al., 2012). Examples are diverse and include testing behaviours in emergency situations in airplanes (Sharma et al., 2011), tunnels (Kinateder et al., 2013), hotels (Kobes et al., 2009), nuclear plants (Jorge et al., 2010), to teach fire-safety skills to children (Smith and Ericson, 2009), rescue training (Li et al., 2005), training workers in manufacturing facilities (Vasudevan and Son, 2011) or common buildings (Balasubramanian et al., 2006; Chittaro and Ranon, 2009; Gamberini et al., 2003; Ribeiro et al., 2012a; J. F. M. Silva et al., 2013; Smith and Trenholme, 2009). Using VR technologies for incident training made possible for Gamberini et al. to observe participants' responses to the outbreak of a fire in a virtual library. Their research showed that participants responded deliberately rather than fleeing in panic — a study impossible in a real-life setting (Gamberini et al., 2003).

In conclusion, VR / VE technology provides the possibility of gaining new insights into human behaviour in dangerous situations that otherwise would have been very difficult to explore.

2.5.2 Serious Games

The growing interest in the use of games and simulations to support learning is evidenced in the literature, and in recent research projects and initiatives (de Freitas, 2006). Games are part of the human heritage and have been used since early times in many civilizations. Their origin belongs to an era preceding that of written records and are a means to understand those times and the relation of men with the environment (Culin, 1894).

The idea of using games for serious purposes goes back to, at least, the XIX century, for military use. Lieutenant Georg Leopold von Reiswitz and his son of the Prussian Army in 1812 devised a set of “war games” for training strategic skills (J. F. Silva et al., 2013). They used the “kriegsspiel” (German word for war games) system for schooling officers on tactical manoeuvres[4].

The SG concept has gained a great prominence in the Digital Games field within the last decade, using appealing software with high-definition graphics and state-of-the-art gaming technology. It presents a great potential of application in a wide range of domains, naturally including social simulation. Contrary to the primary purpose of entertainment in traditional digital games, SGs are designed for the purpose of solving a problem. Although they can be and are indeed expected to be entertaining, their main purpose is to train, educate, investigate, or advertise. Sometimes a serious game will deliberately sacrifice fun and entertainment in order to make a point serious (Ribeiro, 2012).

While a game is an “*artificially constructed, competitive activity with a specific goal, a set of rules and constraints that is located in a specific context*” (Hays, 2005), SGs refer to videogames whose application is focused on supporting activities such as education, training, health, advertising, or social change. SGs are used for rapid prototyping applications that aim for other purposes rather than mere entertainment, taking advantage of the use of appealing high-definition graphics and state-of-the-art software gaming technology. Such purposes include education as well as training. This term was presented by Clark Abt (Abt, 1970) long before the use of computer games for entertainment.

[4] http://kriegsspiel.org.uk/

Despite this fundamental difference, however, even videogames designed for nothing more serious than mindless entertainment have a learning objective, at least at the beginning: teach the player how to play the game. These games also employ pass/fail mechanisms no less rigorous than many college entrance exams. This may come as a surprise to many game developers (Michael and Chen, 2005).

Christian Loh et al. suggest that games can be used for the rationale for quantitative analysis in games, as well as a method to collect in situ game data for that purpose, using a new design framework known as “Information Trails.” This approach made use of gamers’ actions within the game as the basis for assessment of their learning (Loh et al., 2007).

SGs are nowadays used in a variety of applications including education, training, health, advertising or social change (Chen and Michael, 2005; Rossetti et al., 2013; Susi et al., 2007) in diverse domains from military (Caird-Daley and Harris, 2007) to the industry, encompassing medicine, aerospace, advanced sports (e.g. formula 1), among many others (Kirriemuir and McFarlane, 2004). According to Freitas (de Freitas, 2006), combining SGs with other training activities include benefits such as: the learners’ motivation and completion rates are higher; possibility of accepting new learners; having the chance of creating collaborative activities; learning through doing and acquiring experience.

2.5.3 Gamification

According to (Huotari and Hamari, 2012), the term ‘Gamification’ was first used in 2008 in a blog post by Brett Terill, describing the term as “*taking game mechanics and applying them to other web properties to increase engagement*.” To a more widespread industry use the term came to its current form ‘gamification’ during 2010 as “*the use of game design elements in non-game contexts*” (Deterding et al., 2011).

Another aspect is that a great deal of gamification implementations aim towards goals of marketing for measuring sales figures, “clicks” and general retention of users (Huotari and Hamari, 2012). However, these authors claim that if we accept that gamification aims to create “gameful” experiences, then the successfulness of gamification should also be measured through same measurement instruments as games are.

Rossetti et al. (2013) suggest that “*gamification is an important instrument towards behaviour persuasion*,” in the perspective that it has the potential to influence behaviour in the long term.

2.6 Behaviour Elicitation

2.6.1 Knowledge Elicitation

Knowledge elicitation is related with the ways of collecting from human source information relevant to some application or domain. According to the MacMillan Dictionary[5], "elicitation" is the process of getting information from someone. To what our research is concerned, we aim to elicit behaviour from experts or common people on their behaviour when in the presence of fire, at a building.

Table 2.2– Varieties of knowledge elicitation techniques grouped by families (adapted from Cooke, 1994)

Family	Techniques	Methods
Observation and interviews	Observations	Active participation; focused observation; structured observation
	Interviews	Unstructured interviews Structures interviews (focused discussion; teach back; role play; twenty questions; Cloze experiment; Likert scale items; question answering protocols; questionnaires; group interview techniques) Automated interviewing tools
	Task Analysis	Functional flow analysis; operational sequence analysis; information flow analysis; interaction analysis; job analysis; timeline analysis; cognitive task analysis
Process tracing	Verbal reports	Verbal on-line: Self-report (talk-aloud; think aloud; self-critiquing /eidetic reduction); Shadowing Verbal off-line: stimulated recall; retrospective/aided recall; interruption analysis; critical retrospective; group discussion
	Non-verbal reports	
	Protocol analysis	Content analysis; discourse/conversation/ interaction analysis; grounded theory; automated protocol analysis tools
	Decision analysis	Elicitation estimations of probability and utility; statistical modelling/policy capturing
Conceptual techniques	Concept elicitation methods	Structured interviews (concept listing; chapter listing; interview transcription); Concept elicitation with repertory grif (laddering; triad comparison / triad elicitation)
	Data collection methods	Rating & ranking (paired comparisons; magnitude estimation; controlled association; reference ranking) Repertory grid Sorting (Q sort; repeated sort/multiple Q sort; hierarchal sort; multidimensional card sorting) Event co-occurrence/ transition probabilities Correlation / covariance
	Structural analysis	Multidimensional scaling Discrete techniques (clustering, network, scaling) Direct elicitation of structure (drawing closed curves; free association; graph construction; question-answering) Interpretation of the structure (guided interview, identifying aspects of the representation; comparing two or more representations)
	Automation of conceptual techniques	Data mining; machine learning;

[5] http://www.macmillandictionary.com/dictionary/british/elicitation (consulted on August 28th 2014)

Elicitation is a noun related to the transitive verb elicit[6]: 1) to draw forth or bring out (something latent or potential); 2) to call forth or draw out (as information or a response). In Portuguese the translation is the verb "*eliciar*"[7] which has a different meaning, related with expelling or exorcism as well as getting some sort of information or response.

The advent of Artificial Intelligence raises a great number of challenges. One of them is related to the way how knowledge is represented and the general processes operating on that representation. The process of knowledge elicitation is related with the ways of collecting from a human source information that is thought relevant to some application or domain (Cooke, 1994). Some of the techniques for elicitation are depicted in Table 2.2. For decision-support systems, for instance to understand how customers choose products and make decisions, the elicitation of user's preferences is a primary issue for which various techniques may be used (Chen and Pu, 2004).

The knowledge elicitation phase of expert system development is considered to be a major hurdle especially as the expert knowledge is multifaceted since it has both explicit and objective knowledge as well as implicit (Crandall, 1989). Of the many techniques available, there is a methodology called "Delphi process" that is used for the elicitation of knowledge from experts of a certain field (Brown, 1968). This method has been used to extract the knowledge of one or more experts with the goal of establishing a set of concepts and facts much needed to feed agents (Lawson, 2011).

2.6.2 Human Behaviour Elicitation

Capturing behaviour characteristics of humans to grow and breed artificial societies of agents is a laborious and not so easy task. Purposes of this knowledge may be used in a variety of areas, such as Artificial Transportation Systems (ATS) or to evaluate in-vehicle information systems (IVISs) (Gonçalves et al., 2012). The mechanisms underlined within this concept are to envisage the "*adequate means to capture the semantics of decisional processes as an attempt at disclosing cognitive abilities*" (Rossetti et al., 2013).

The problem of understanding the emotional context towards the creation of a model that incorporates emotions and the behavioural aspects of humans in the decision making process leads to the concept of Emotional Elicitation (Sarmento, 2004). This aspect is of paramount

[6] "Elicit." *Merriam-Webster.com*. Merriam-Webster, n.d. Web. 18 Aug. 2014. <http://www.merriam-webster.com/dictionary/elicit>.
[7] http://www.priberam.pt/dlpo/eliciar

importance when trying to envisage a framework composed of intelligent agents mixed in a certain environment where the individual and collective behaviour has sometimes conflicting goals and approaches to achieve them. To model such agents, the knowledge on the underlying mechanisms and the insights of their inner aspects that will ultimately influence their behaviour must be available and be trustworthy. Humans are much affected by emotions and emotional states, and these are intimately related with the surroundings that will somehow interfere in the decision-making processes that are so unpredictable. Sarmento defends that agents' trying to mimic humans when incorporating some sort of emotions must have internal states that represent the following three aspects: i) goals; ii) capabilities; ii) environment aspects or events that might affect emotions.

Being a multi-disciplinary problem, behaviour elicitation is related with psychology as well as engineering, and with connections to many other scientific areas such as sociology, artificial intelligence and statistics.

2.6.3 Behaviour Elicitation in the Context of Fire Safety and Egress

The domain of fire safety is utterly dependent of human behaviour, both in its origin as well as during its development (Horiuchi, 1989). Particularly the evacuation process in which occupants must leave whatever activities they are engaged to move as quick as possible towards the safest and nearest exit. It is commonly noted that the human behaviour is of paramount importance for the outcome of such process (Galea, 2012; Kobes et al., 2007; Kuligowski, 2011; Pigott, 1989).

At LIACC, for the past couple of years, this goal of creating a set of tools for eliciting human behaviour in emergency situations has been pursued (Almeida et al., 2014d, 2013; Cordeiro et al., 2011b; J. F. M. Silva et al., 2013; Vasconcelos et al., 2012).

Some researchers, such as (Kobes et al., 2009; Lawson et al., 2013) have used VR to recreate dangerous environments without having to risk the lives of the participants to the experiments.

However, despite experiments made by researchers such as (Andrée et al., 2013) or (Kinateder et al., 2014) one critical issue persists: data on pedestrian movement in both normal and emergency situations is scarce and this is considered to be one of the great challenges for the 21st century in what concerns evacuation simulators and pedestrian models (Galea, 2012). Moreover, the existing models are more focused in the movement and locomotion aspects as opposed to the behavioural aspects that govern pedestrians and evacuees.

2.7 Application domain: evacuation scenarios

2.7.1 Fire Risk and Building Occupants' Safety

Fire risk is the leading hazard for the safety of buildings and, consequently, for other risk protections. The risk of a tragedy due to a fire in a building increases significantly as the number of their occupants' rises (Sime, 2001; Watts and Hall, 2002). Buildings nowadays may have hundreds or thousands of occupants. Many of them are not aware of the architectural layout or the safest and rapid exit from their standing point (Gwynne et al., 1999). When facing an emergency situation, such as fire, explosion or other threats, having safe exits towards the outside is imperative. And in complex and large buildings the evacuation routes are sometimes not obvious for occupants (Graat et al., 1999). Evacuees spend more time than expected in searching the right way, sometimes missing the evacuation signage and at other times not following the expected behaviour that architects and planners had in mind when designing the building (Ozel, 2001).

To assess the fire risk of a building is consequently very important to determine the level of safety for their occupants. According to (Watts and Hall, 2002) fire risk analysis (FRA) "*is a scientific process, closely linked to calculations based on proven relationships and the collection and analysis of valid and appropriate data, to describe the form, dimension, and characteristics of the fire risk*".

FRA models such as the Gretener, developed by the Swiss engineer in the 1960's, or the more recent FRAME (Seito et al., 2008), are very popular among fire safety engineers and risk analysts (Miguel et al., 2010). Robert Fitzgerald developed his own model, after years of practice and experience as a fire safety engineer, professor and fireman (Fitzgerald, 2004). Coelho proposed the MARIE model (Coelho, 1997) as a framework to assess building FRA; however a computer implementation, even if some attempts were made, is still not available and has revealed to be a very complex task.

The method recommended by NFPA for assessing the safety of building occupants is the ASET/RSET (Babrauskas et al., 2010; SFPE, 2002). It consists on determining the Available Safe Egress Time (ASET), basically the time interval between the beginning of the fire and when the conditions of the building become untenable for human life; then compare it with the Required Safe Egress Time (RSET), the time necessary by the occupants to leave the building safely (Lovreglio et al., 2015). This method is the one preferred by both designers and authorities to establish the safety level of a building.

2.7.2 Prescriptive Fire Codes versus Performance-Based Design

Fire safety design much depends on building codes, standards of practice and insurance requirements (Fitzgerald, 2004). Fire codes are traditionally prescriptive, providing exact rules and solutions for each possible situation. In more recent years, Performance-Based Design (PBD) applied to fire safety has been used in more complex buildings (Heath et al., 2009), like the new skyscrapers in emergent countries, facilities for the Olympic Games in China, new Dubai buildings, and among other examples, "*Casa da Música*" in Porto, Portugal. These buildings pose new challenges to Architects, Engineers and Authorities, since the traditional fire codes are not applicable. In PBD, rather than applying the rules directly, the challenge is to define the safety goals and implement measures that accomplish them. Typically the objectives are: insure building occupants' life safety, provide adequate protection for goods inside and, in case of fire, create conditions for fire-fighters to work safely.

A unified fire code, released in Portugal in 2008, concerns not only new buildings but also applies to existing ones (Portugal, 2008a, 2008b). One novelty is the possibility of using PBD (under certain conditions) for special or complex buildings where estimating the evacuation time is a fundamental problem.

The core issue of PBD when assessing the safety of a building lies in a detail about the estimation of two times; the RSET must be lower than ASET in order to consider the building safe for its occupants (Lovreglio et al., 2014).

2.7.3 Other Risks Beside Fire Requiring Building Evacuation

The risks requiring building evacuation can be categorized according to the following list:

- Natural hazards: flooding, thunderstorm, earthquake, hurricane or cyclone, wildfire
- Technical: fire, gas leak, explosion, power failure, chemical leakage, radiation
- Human: terrorist attack, bomb threat, accidental or intended failure leading to fire, toxic or chemical leakage, social unrest or riots.

Emergency plans have to address the following goals to be achieved: i) life safety; ii) assets protection including cultural heritage; iii) ensuring normal activities' continuity. The evacuation plans, an important part of emergency plans, must address the following aspects:

- For each location/compartment/floor define the egress route;
- If possible, identify alternate routes if the main one becomes blocked;

- Define staged evacuation phases in large facilities;
- Have an evacuation leader coordinating all evacuation groups;
- Assign one team leader to each evacuation group;
- Ensure good communication facilities for coordination purposes;
- Assign a liaison officer to receive and debrief the emergency responders (firemen, paramedics, police or civil protection personnel);
- Provide a "crisis room" adequately equipped with communication (telephones, mobiles, radios, CCTV, etc.) as well as plans with all facility floors and safety means;
- Define meeting point or points where evacuees must concentrate for people counting.

Evacuations are planned in levels. Some emergencies may require the evacuation of only a small area near the problem, others might require the entire building to be evacuated and larger emergencies might require the entire site to be evacuated as well (Almeida et al., 2014b).

2.7.4 Fire Drills

The main goal of Fire Drills (FD) is to train evacuation procedures. Evacuation or egress, as it is also known, consists on the process of the occupants of a building exiting it to a safer place, normally outside. Occupants should regroup near a pre-defined place called "meeting point" (Colonna, 2001) where evacuees must concentrate for people counting.

Fire Drills are a means to:

a) Train occupants and evacuation teams' procedures;
b) Evaluate their behaviour and coordination;
c) Test the validity of emergency and evacuation plans for different emergency scenarios.

An effective fire drill starts with planning. First, possible hazards are identified and the adequate actions for each must be detailed. This is part of the risk assessment and emergency planning. Evacuation is one of the possible actions. It can be a total or partial site evacuation. For instance, in large facilities such as hospitals or tall buildings, the evacuation must be phased. It might be a horizontal evacuation, within the same floor or a vertical one, when people are moved to different floors, or even towards the outside. In hospitals, horizontal evacuation is the preferred method, from one ward to a safe area taking advantage of fire barriers.

There are different kinds of evacuation exercises: i) small scale, with just some part of a building or campus is affected; ii) training staff in fire protection, where some tutorial is provided and real fire extinguishing using portable extinguishers or fire hoses and their use are evaluated; iii) large scale fire drills with the co-operation of fire fighters, police, ambulances and other emergency responders (Hallberg, 1989). After the realization of a Fire Drill, participants and managers de-brief, pointing out what were the successful events and the ones that will require a review.

In many countries FDs are mandatory for certain types of buildings with a minimum periodicity. Legislation addressing the need of fire safety services at hospitals, schools and public buildings was only published in Portugal in 2002. Later, with the unified code (Portugal, 2008a, 2008b), the life cycle after the construction phase and fire permit, was addressed. Emergency plans and safety procedures, including systems management, buildings exploitation, training and Fire Drills (FD) are now covered by the fire code.

FDs became mandatory at least every two years in buildings with higher fire risk depending on the use type and risk class[8]. The implementation in many organizations of quality systems (e.g. ISO 9001) requiring the existence of emergency plans, has also boosted the implementation of FD as part of the fire safety management (Colonna, 2001). However, more important than legislation itself is to implement a safety culture and make it part of daily routine.

In this area there is still a lot to be done. Schools should lead by integrating fire safety culture in the curricula and academic projects. Companies and organizations should develop training sessions and set up at least one FD per year. Public services should also be aware of fire safety requirements and be the first to implement the fire code (Almeida and Coelho, 2007).

FDs are not yet as common in Portugal as in other developed countries, where FDs are frequent and a great part of the population is familiarized with fire safety concepts. The impact of implementing a safety culture in organizations and buildings management would certainly have an important impact on the economy due to reducing the losses of lives and goods originated by fire, and also for creating a new set of activities and professions related therewith (Almeida, 2008).

2.7.5 Estimating Building Evacuation Time

As previously referred (see 2.7.1 and 2.7.2), determining the ASET and RSET is fundamental to assess the safety level of a building. Whilst ASET depends on the fire development, the fuel load,

[8] Portuguese fire code classifies buildings according to their use, in a four risk level scale.

heat release rate (HRR) and other fire related variables, RSET is basically the time needed by evacuees to safely leave the building.

So, RSET depends upon evacuees' behaviour, during the pre-evacuation time (PET) and the movement time (MT). Typically RSET is computed using the following equation:

$$RSET = AT + PET + MT \tag{1}$$

Where AT is the time interval which starts with the ignition of the fire and ends when the automatic fire detection siren alarm sounds and alerts the evacuees. The PET value corresponds to the time interval starting with the alarm and ending when an evacuee starts moving toward the building exit. Finally the movement time (MT), also known as travel time (Klingsch et al., 2010; Tanaka, 1991), is the time needed by an evacuee to reach the building exit, starting from the location where the movement started. So, the total time of RSET depends not only on the movement speed, but also on the choices made during the travel, including the time needed to start moving.

Therefore, assessing the level of safety of a particular building requires an adequate estimation of the ASET and RSET values. And, as evidenced, much of the data needed to calculate, particularly, the RSET, depends on human behaviour. This is why it is so important to have more insight on the evacuees' decision making process and behaviour during the evacuation, otherwise any RSET estimation might fail, and a building considered safe, might not be as safe as expected. Ultimately, this singular aspect may cost lives in case of a fire.

2.8 Summary

After this chapter, the reader will be acquainted with Social Simulation and its purpose, as well as the relation between artificial intelligence (AI), intelligent agents and agent-based simulation. All these concepts, along with multi-agent systems (MAS), a subset of AI, called distributed AI (DAI), are necessary to understand how computer modelling and simulation is used for tackling problems such as pedestrian modelling and simulation.

Section 2.4 covers various aspects and phenomena related with pedestrians: applications, formations, modelling techniques and the problem of human behaviour conditioning the prediction of pedestrians, both in normal and emergency situations. Some examples are cited with victims, historic and recent illustrations.

Section 2.5 explains synthetically how virtual worlds are implemented in computers, using concepts such as virtual reality and environments, CAVEs, videogames, and their relation with Serious Games. SGs can be and are effectively used for simulation in a wide array of applications. The latest trend consists on the gamification concept to motivate and engage players.

Behaviour elicitation is the key subject of Section 2.6. Some techniques for knowledge elicitation in general and more specifically for human behaviour elicitation are presented. This problem is contextualized in the AI domain; since reliable knowledge for the creation of valid models of human behaviour is unquestionably needed and new methodologies for eliciting such knowledge are required as well. Again, no instance linking SGs and behaviour elicitation was found, pointing out that this combination is a novel situation.

Finally, Section 2.7 describes the context of fire safety and emergencies situations, and explains why this subject is of high importance, namely to protect and save lives. Prescriptive and performance based approach for fire safety design is introduced. And why it is so important to assess the evacuation time of buildings, namely the ASET and RSET, for which evacuation simulators are the best option available today. The drawbacks of those simulators, detailed in the next chapter, arise mainly from the lack of human reasoning process. That is why Kuligowski research is so critical.

Next chapter will present a literature review more focused on experiments and related work on emergency evacuation simulators, SGs, and experiments using SGs within the evacuation context, as well as behaviour elicitation.

3. Literature Review: Related Work

3.1 Overview

This chapter complements the literature review presented in the previous chapter with focus on the work of researchers that are in some way related to this thesis. It starts with a section presenting an overview of emergency evacuation simulators; then a comparison of the different simulators is presented with the corresponding discussion. This is followed by the taxonomy for training using virtual environments and SGs. Some examples found in the literature of using SGs for simulation, training or behaviour analysis in emergency situations are then presented. This chapter ends with a description of the ongoing research at LIACC, concerning human behaviour in emergency situations, to illustrate inspirational efforts underlying this thesis.

3.2 Emergency Evacuation Simulators

In this section an extensive analysis of the existing Emergency Evacuation Simulators is presented. It starts by explaining the concept, then a taxonomy is described based on two works, one by Kuligowski et al. from NIST (USA) and another from Kady et al., carried out in the UK. Both perspectives are analysed and compared. The ModP simulator developed at LIACC is considered and also included in the analysis.

3.2.1 Evacuation Models

Evacuation models face the challenge of demonstrating that they represent accurately human behaviour in emergency situations, namely when simulating a building's evacuation process. There are several dozens of evacuation simulators (Gwynne et al., 1999; Kady et al., 2009; Kuligowski et al., 2010; Santos and Aguirre, 2004). The portal evacmod.net[9] has a list of 64 evacuation models plus 3 lift/elevator models. Some of them are result of academic work, with no support, and many times not available for third party tests. A few models are free to the public, like FDS+EVAC. Others were developed for commercial use (e.g. Pathfinder). Furthermore, some are only available via a consultancy basis, where the development company will use it by their own experts. In this situation, only the results are given to the user. Availability is also scarce.

[9] http://www.evacmod.net/

Results comparison show important differences. Validation of these models is not provided in many of them.

3.2.2 Taxonomy and Simulators Analysis

For the studies described in this work, the taxonomy devised is detailed and discussed. In the NIST study some sub-classification was added to help clarify the review clustering. The ModP simulator developed at LIACC from 2009 onwards was inserted in both studies using the same criteria presented for the analysis of other models.

One possible categorization of Evacuation Simulation Models (Santos and Aguirre, 2004) is:

- Flow based (e.g. EVACNET)
- Cellular automata (e.g. EGRESS)
- Agent-based (e.g. SIMULEX)
- Activity-based (e.g. Exodus).

3.2.3 The NIST Review

In 2005, Kuligowski, Peacock et al., published a paper called "Review of Building Evacuation Models" comparing the known evacuation simulators (Kuligowski and Peacock, 2005). A revised edition was released in 2010 (Kuligowski et al., 2010). A critical comparison of 26 models is presented, although not all of the models tested are available. While evacuation from buildings is the main focus of that work, many of the models reviewed have the ability of simulating the evacuation process from other types of structures such as elevators. The models are organized in the review by their availability: for general use, on a consultancy basis, and not released. Models no longer in use were excluded from the review. Additionally, models that have not had any peer-reviewed literature published regarding their use or development since 2000 were not included in the last review.

The taxonomy proposed by (Kuligowski et al., 2010) includes the following features:

- **Model availability** – if the model is available for *free* (Y1), by *paying a fee* (Y2), only available for a *consultancy* basis (N1) or *not released* (N2).
- **Modelling method** – *movement* only (M), *movement with some optimization* algorithm (M-O), *behavioural* model (B), *partial behavioural* model (PB), *behavioural* model *with risk assessment* capabilities (B-RA).

- **Model purpose** – *any type* of building (1), *residences only* (2), *public transport stations* (3), *low-rise buildings* under 15 stories (4), *only one route/exit* (5);
- **Type of grid/structure** of the model - *Coarse* network (C), *Fine* network (F) or Cellular Automata, *Continuous* (Co);
- **Type of Analysis** – global or macroscopic (G), individual or microscopic (I);
- **Occupants' view of the building** – complete knowledge of building's exits and routes (G), partial knowledge of building (I);
- **Behaviour of the occupants** - no behaviour (N), implicit (I), conditional or rule-based (C), artificial intelligence (AI), probabilistic (P);
- **Movement of the occupants** - density (D), user's choice (UC), inter-person distance (ID), potential (P), emptiness of next grid cell (E), conditional (C), acquired knowledge (AcK), Unimpeded flow (UnF), cellular automata (CA).
    - *Density* correlation (D): the model assigns a speed and flow based on the density of the space, using the works of Fruin (Fruin, 1987), Pauls (Pauls, 1995, 1980), and studies in former Soviet Union (Predtechenskii and Milinskii, 1978).
    - *User's Choice* (UC): The user assigns manually the speed, flow, and density.
    - *Inter-person Distance* (ID): Each agent has a boundary sphere that requires to have a certain minimum distance from other occupants, obstacles, and components of the building (such as walls, corners and handrails).
    - *Potential* (P): Each grid cell in the space is given a certain number value, or potential, from a particular point in the building that will move occupants throughout the space in a certain direction. Occupants follow a potential map and attempt to lower their potential with every step or grid cell to which they travel. The potential of the route can be altered by such variables as patience of the occupant, attractiveness of the exit, familiarity of the occupant with the building, etc. (which are typically specified by the user).
    - *Emptiness* of next grid cell (E): In some models, the occupant will not move into a grid cell that is already occupied by another occupant. Therefore, the occupant will wait until the next cell is empty, and if more than one occupant is waiting for the same cell, the model will resolve any conflicts that arise when deciding which occupant moves first.
    - *Conditional* (C): Movement throughout the building is dependent upon the conditions of the environment, the structure, the other evacuees, and/or fire situation.

  - *Acquiring Knowledge* (AcK): Movement is based solely on the amount of knowledge acquired throughout the evacuation. For this model, there is no real movement algorithm because evacuation time is not calculated; only areas of congestion, bottlenecks, etc.
  - *Unimpeded Flow* (UnF): For this model, only the unimpeded movement of the occupants is calculated.
  - *Cellular Automata* (CA): The occupants in this model move from cell/grid space to another cell.
- **Incorporation of fire effects** - the model cannot incorporate fire data (N), the model can import fire data from another model (Y1), the model allows the user to input specific fire data at certain times throughout the evacuation (Y2), the model has its own fire model (Y3);
- **CAD importing** – states if the model permits importation of computer-aided design (CAD) drawings, yes (Y), no (N);
- **Visualization methods** – no (N), 2-dimension visualization available (2D), 3-dimension visualization available (3-D);
- **Validation methods** - validation against *Codes* (C); validation based on *Fire Drills* or other people movement experiments/trials (FD); validation against literature on *Past Experiments*, like flow rates, etc. (PE); validation against *Other Models* (OM); *Third Party* validation (3P); *No* validation work could be found regarding the model (N).

Table 3.1 shows the results comparing the 26 models using the aforementioned taxonomy. At the end, Modp, the simulator developed at LIACC (Aguiar et al., 2010; Aguiar, 2010; Esteves, 2009; Esteves et al., 2009) was added to the comparison. This model is not publicly available (N2), modelling is based on movement alone (M), was designed for transportation purposes, both indoor and outdoor, and buildings too (1,3). Movement is of the continuous type. Aimed at microscopic analysis (I), occupants do not have knowledge of the site layout (I) and use Artificial Intelligence (AI) for the steering, although very limited complex BDI model was planned to be implemented by (Esteves, 2009). No fire data in the model (N) and no CAD importer (N). Visualization permitted is 3D with a 2D analysis module. No validation of the model was made so far (N).

Table 3.1 – Emergency Evacuation Simulator's comparison (adapted from Kuligowski et al., 2010)

Model	Availability	Modelling Method	Purpose	Grid/Structure	Type of Analysis	Occupants Building Knowledge	Occupants behaviour modelling	Occupants movement	Fire effects	CAD importing	Visualization method	Validation methods
EVACNET4	Y	M-O	1	C	G	G	N	UC	N	N	N	FD
WAYOUT	Y	M-O	5	C	G	G	N	D	N	N	2D	FD
STEPS	Y	B	1	F	I	I	C,P	P,E	Y1,Y2	Y	2D/3D	C,FD,PE
PEDROUTE	Y	PB	3	C	G	G	I	D	N	Y	2D/3D	N
Simulex	Y	PB	1	Co	I	I	I	ID	N	Y	2D	FD,PE,3P
GridFlow	Y	PB	1	Co	I	I	I	D	N	Y	2D/3D	FD,PE
FDS+Evac	YF	PB	1	Co	I	I	I,C,P	ID	Y3	Y	2D/3D	FD,PE,OM
Pathfinder 2009	Y	PB	1	Co	I	G	I	D,ID	N	Y	2D/3D	C,FD,PE,OM
SimWalk	Y	PB	1,3	Co	I	I	C,P	P	N	Y	2D/3D	FD,PE,3P
PEDFLOW	Y	B	1	Co	I	I	C,P	ID	Y2	Y	2D/3D	PE
PedGo	Y	PB/B	1	F	I	I,G	I/C,P	P,E,CA,C	Y2	Y	2D/3D	FD,PE,OM,3P
ASERI	Y	B-RA	1	Co	I	I	C,P	ID	Y1,Y2	Y	2D/3D	FD,PE
BuildingEXODUS	Y	B	1	F	I	I	C,P	P,E	Y1,Y2	Y	2D/3D	FD,PE,OM,3P
Legion	Y	B	1	Co	I	I	AI,P	ID,C	Y1	Y	2D/3D	C,FD,PE,3P
SpaceSensor	Y	B	3	Co	I	I	C,P	C,AcK	N	Y	2D/3D	FD,OM
EPT	Y	B	1	F	I	I	AI	UC,C	Y2	Y	2D/3D	FD
Myriad II	Y	B	1	C,F,Co	I	I	AI	D,UC,IP,AcK	Y1	Y	2D/3D	PE,3P
MassMotion	Y	B	1	Co	I	I,G	AI,P	C	N	Y	2D/3D	C,FD,PE,OM
Pathfinder	N1	M	1	F	I	G	N	D	N	Y	2D	N
ALLSAFE	N1	PB	5	C	G	G	I	UnF	Y1,Y2	N	2D	OM
CRISP	N1	B-RA	1	F	I	I	C,P	E,D	Y3	Y	2D/3D	FD
EGRESS 2002	N1	B	1	F	I	I	C,P	P,D,CA	Y2	N	2D	FD
SGEM	N1	PB	1	Co	I	I	I	D	N	Y	2D	FD,OM
EXIT89	N2	PB	1	C	I	I	I/C,P	D	Y1	N	N	FD,3P
MASSEgress	N2	B	1	Co	I	I	C,AI	C	N	Y	2D/3D	PE,OM
EvacuationNZ	N2	B	1	C	I	I,G	I,C,P	D,UC	Y2	Y	2D	FD,PE,OM
ModP (a)	N2	M	1,3	Co	I	I	AI	ID, UnF	N	N	2D/3D	N

(a) not in the original NIST studies

3.2.4 The Kady's Review

The review by (Kady et al., 2009) includes 62 different evacuation models. Research focus was on the data used in those models, specifically on movement speed. The main goal was to find the theoretical and empirical background used to support the occupants movement models. In that study, the taxonomy is three-fold: (1) movement condition/type; (2) speed of movement value used; (3) sources (studies or predetermination by model developers).

Regarding the movement issue, the study found various situations, also derived from the theoretical studies used. The simpler models have a fixed velocity movement, whilst in the more complex models the speed varies with density, normal or emergency movement, gender and age, among other factors like the hazards of fire and smoke.

Table 3.2 - Movement conditions/type, values and source for Evacuation Simulators (adapted from Kady et al., 2009)

Model	Movement Condition/Type	Value (m/s)	Source	Observations
STEPS	walk	1	Developers predetermination	
Simulex	walk	0.8 ~ 1.7	Aldo et al.	walking speed varies
	u (male)	0.15 ~ 1.55		
	u (female)	0.95 ~ 1.35		
	u (elderly)	0.6 ~ 1.2		
	u (child)	0.5 ~ 1.1		
GridFlow	unimpeded	1.19 ± 0.3	Nelson & MacLennan	
EXODUS	fast walk	1.5	Jin	
	walk	1.35		
	leap	1.2		
	crawl	0.3		
EGRESS 2002	unimpeded	0.9 ± 0.424	Predtechenskii & Milinskii	
	haste factor (emergency)	1.5		
	haste factor (non-emergency)	0.6		
SGEM	walk	1,40	Developers predetermination	
EXIT89	unimpeded	1,36	Predtechenskii & Milinskii	
MASSEgress	average walking (median)	1.3	Thompson et al.; Eubanks & Hill	walking & running
	average walking (male)	1.35		
	average walking (female)	1.15		
	average walking (child)	0.9		
	average walking (elderly)	0.8		
	max.flat running (median)	4.1		
	max.flat running (male)	4.1		
	max.flat running (female)	4.1		
	max.flat running (child)	3.4		
	max.flat running (elderly)	2.75		
FDS+Evac (a)	unimpeded	varies	Helbing et al.	social forces model
ModP(a)	unimpeded	varies	Developers predetermination	various agents types can possibly coexist

(a) not in the original Kady, Gwynne et al. studies

Movement type can be of two types: walking speed (w) or unimpeded (u). In this last situation movement depends on the “comfort zone” radius width, individuals cannot overlap the others comfort zones. This radius varies, diminishing as the surrounding conditions get worse (in the case of a fire, for instance). Social forces models like Helbing's (Helbing and Molnar, 1995) are also used. Speed value is thus variable and depending on several factors.

This work refers as sources basic research on the pedestrian movement such as the studies of Fruin, Pauls, Predtechenskii and Milinskii (Fruin, 1987; Pauls, 1980; Predtechenskii and Milinskii, 1978). Other authors cited are Aldo et al., Nelson & MacLennan, Jin, Thompson et al., Eubanks & Hill. These aforementioned are cited in Coelho's research (Coelho, 1997) and Kuligowski's literature review (Kuligowski, 2003), just to cite two examples.

Although the work presents a review of 62 different evacuation models, only 20 of those models are summarized in the comparison table, due to lack of information (Kady et al., 2009). And of these, only 8 models are common with NIST studies (Table 3.1). FDS+EVAC model (Korkhonen & Hostikka, 2010) was added since data for this comparison is available (Gissi et al. 2009). Similarly to the NIST study aforementioned, ModP was also added (seeTable 3.2).

FDS+EVAC uses a combination of several models, namely the Helbing's social forces model. ModP uses unimpeded movement, having Aguiar (2010) included different agent types to be predefined thus permitting to model groups like children, women, men, and elderly, varying the comfort radius and maximum speed parameters.

3.2.5 Combining the NIST and Kady's Reviews

NIST studies evaluate 26 models, whilst the work by Kady, Gwynne et al. has a review of 62 different evacuation models, reducing the final result to 20. Only 8 are common. The FDS+EVAC and ModP models were added as well. A combination of both studies and taxonomies is presented in Table 3.3.

Table 3.3 – Combination of NIST and Kady studies plus FDS+EVAC and ModP

Model	Availability	Modelling Method	Purpose	Grid/Structure	Type of Analysis	Occupants Building Knowledge	Occupants behaviour modelling	Occupants movement	Fire data	CAD importing	Visualization method	Validation methods	Movement Condition/Type	Value (m/s)	Source
STEPS	Y2	B	1	F	I	I	C,P	P,E	Y1,Y2	Y	2D/3D	C,FD,PE	w	1	Developers predetermination
Simulex	Y2	PB	1	Co	I	I	I	ID	N	Y	2D	FD,PE,3P	w,u	varies	Aldo et al.
GridFlow	Y1	PB	1	Co	I	I	I	D	N	Y	2D/3D	FD,PE	u		Nelson & MacLennan
EXODUS	Y2	B	1	F	I	I	C,P	P,E	Y1,Y2	Y	2D/3D	FD,PE,OM,3P	w	varies	Jin
EGRESS 2002	N1	B	1	F	I	I	C,P	P,D,CA	Y2	N	2D	FD	w,u	varies	Predtechenskii & Milinskii
SGEM	N1	PB	1	Co	I	I	I	D	N	Y	2D	FD,OM	w	1,40	Developers predetermination
EXIT89	N2	PB	1	C	I	I	I/C,P	D	Y1	N	N	FD,3P	u	1,36	Predtechenskii & Milinskii
MASSEgress	N2	B	1	Co	I	I	C,AI	C	N	Y	2D/3D	PE,OM	w	varies	Thompson et al.; Eubanks & Hill
FDS+Evac	Y1	PB	1	Co	I	I	I,C,P	ID	Y3	Y	2D/3D	FD,PE,OM	u	varies	Helbing et al.
ModP	N2	M	1,3	Co	I	I	AI	ID, UnF	N	N	2D/3D	N	u	varies	Developers predetermination

3.2.6 Discussion

Comparing the two studies and the taxonomies, it is possible to define what features are more important and the ones that models should have.

Starting with *availability*, only two of the models presented are free for use, EVACNET4 (Hieyaniemi et al., 2004) and FDS+EVAC, albeit the first one is very basic. The other models are not available to the general public, either due to their academic nature or commercial reasons.

The *modelling methods* vary, from the movement with some optimization (M-O) to the more complex behaviour with risk-assessment (B-RA). It is suggested that the best option is the risk-assessment (B-RA) used by ASERI and CRISP. ModP uses basic modelling (M); agents try to reach their goal (a known location) using trial an error method and collision avoidance, even though some other heuristics and methods are proposed (Aguiar, 2010; Esteves, 2009).

The *purpose* of the simulation, for most of the models, is valid for any type of building, except ALLSAFE and WAYOUT (which only allow one route/exit of the building), PEDROUTE and

SpaceSensor, designed for public transport stations. Simwalk is also able to model public transport stations. ModP initial purpose was to be used as a pedestrian simulator for both indoor and outdoor, including multimodal transport facilities.

As for the *grid/structure,* continuous (Co) is the best option to use. Continuous is more realistic since cell movement has only eight directions whilst in continuous free movement any direction is possible. Analysis permitted by models should be both macro and microscopic (G and I). Occupants model view in most cases should be partial (I) since in complex buildings, occupants are not aware of their full layout.

Occupants behaviour varies over the models analysed. A combination of AI techniques, probabilistic and conditional, should be the option for the ideal model, including behavioural models. Occupant's movement in the ideal model should also combine the various possibilities, considering density, speed, and all factors that might affect speed (gender, age, normal or emergency situation, presence of smoke, fire, visibility).

Fire data is important for the realm of the analysis. Without it, only fire drills can be simulated. The only CFD model freely available is FDS from NIST.

CAD importing is another feature with relevance for the modelling phase of the simulation process. Many of the models analysed provide this feature as standard. However the amount of time and effort needed to accomplish this modelling step is not quantified. Typically this is an area that challenges the modeller patience because automatism in the conversion mechanism is not perfect and information is lost in the process.

The visualization modules should comprise both 2D and 3D possibilities. For data analysis, 2D is better suited, for bottleneck point's identification, also for the arching, clogging and herding investigation. For the sake of realistic appearance, 3D is important since it gives a better view of the scenario.

Validation methods, and data sources used for modelling construction is of upmost importance. As stated in Kady, Gwynne et al. study, not all models are validated. And the movement studies used by those models are old, some with no statistical relevance. This permits to conclude that the influence of the data used, will have a significant impact on the validation of these models towards their acceptance by both the academic society and practitioners.

3.3 A Taxonomy for Training Using Virtual Environments and Serious Games

Games and simulators can be used for cheaper training rather than using traditional methods. Flight simulators, for instance, do not replace actual flying, but are commonly used for training pilots to react accordingly in certain situations that are hard to reproduce in real life, such as emergency landing. Besides, pilots can practice and gain mileage and these systems are also used to endorse the issuing of flying permits and as a means of certification.

3.3.1 A Behaviour Taxonomy for Describing Human Tasks

The issue of determining a set of skilled behaviours for the acquisition, performance, and retention, constitutes a fundamental prerequisite to the effective operation of any man-machine system (Fleishman, 1967a). Psychologists have studied human learning and performance in many contexts and have accumulated vast quantities of data. And yet, every time as new systems are conceived for uses such as the exploration of space, defence, industry or even entertainment, it turns out that much of the accumulated data and experience are largely inapplicable and that the problems of skill identification, training, and performance must be restudied almost from scratch. Why does this happen so often? Basically, each new system, gear, machine or computer software differs from others with respect to application, mission, and technology.

Task and systems are seldom similar or have identical requirements. And previous training device or simulator quite seems to meet the requirements of any system except the one for which it was developed. Is it reasonable to conclude that the tasks of men in systems are so varied that there are no common dimensions with respect to the basic abilities required, the types of training needed for job proficiency, or the degradation of skilled behaviour under given environmental conditions?

To answer this last question, for the American Air force and NASA space program back in the 1960's psychologists like Fleishman have developed a series of tests and investigated hundreds of different tasks administered to thousands of subjects. The purpose was to define the fewest independent ability categories which might be most useful and meaningful in describing performance in the widest variety of tasks (Fleishman, 1967b).

Their research ended categorizing a series of psychomotor factors in the area of physical proficiency such as control precision, limb coordination, response orientation, reaction time, speed of arm movement, manual dexterity, arm-hand steadiness, aiming, among many others.

Some of these were particularly important for flight and astronaut pilots (Fleishman, 1967a). And were the basis for the Human-Computer Interaction (HCI) domain, so important in the videogame development as well as for training humans using simulators in a array of situations.

Another work by (Cowell and Cowell, 2009) classifies nonverbal behaviour for computer characters in the following categories:

- Facial expressions: smiles, eye brow-raised, head movements, etc;
- Eye contact: eye contact with the user or player, blinking, looking down or away;
- Gestures: body language, hands and elbows posture, relaxed or nervous gestures;
- Posture: mainly related to shoulders and back posture, straight or curved.

These authors describe some application to analytical games for the development of realistic environments.

3.3.2 A Taxonomy of Goal-Oriented Action in Virtual Reality Training Environments

With the shift of training scenarios to virtual worlds and assessment being an inevitable part of any teaching and learning process, sophisticated evaluation methods to analyze action-sequences of learners according to reference solutions defined by experts and provide automated formative feedback are needed. An action taxonomy to classify recognized actions performed by the user in the virtual world is proposed by (Fardinpour and Reiners, 2014). Their work mostly relies of goal-oriented actions in virtual training environments assessing knowledge of students based on their goal-oriented actions reflected by their avatars in virtual training environments.

This research has identified the following interactions within virtual training environments: avatar-avatar; avatar-environment (and vice-versa); avatar-objects (and vice-versa). Depending on the domain applications there might be different kinds of interactions between the avatars, environment and objects. Nevertheless, in virtual worlds, interactions may include intelligent bots as well (Trajkovski and Collins, 2009). This is a field of on-going research for which no definitive taxonomy exists and each application or research group uses their own approach.

3.3.3 Towards a Taxonomy of Agent-Based Simulation Models

Agent-based simulations are used increasingly in a wide variety of domains. For instance, in environmental management some authors proposed a simple and preliminary taxonomic structure that classifies models by their requirements (see Figure 3.1). The proposed structure considers three levels for decision-making process: micro-level, social interaction and adaptive (Hare, 2004). For each a set of techniques are required and thus must be provided to the intelligent agents.

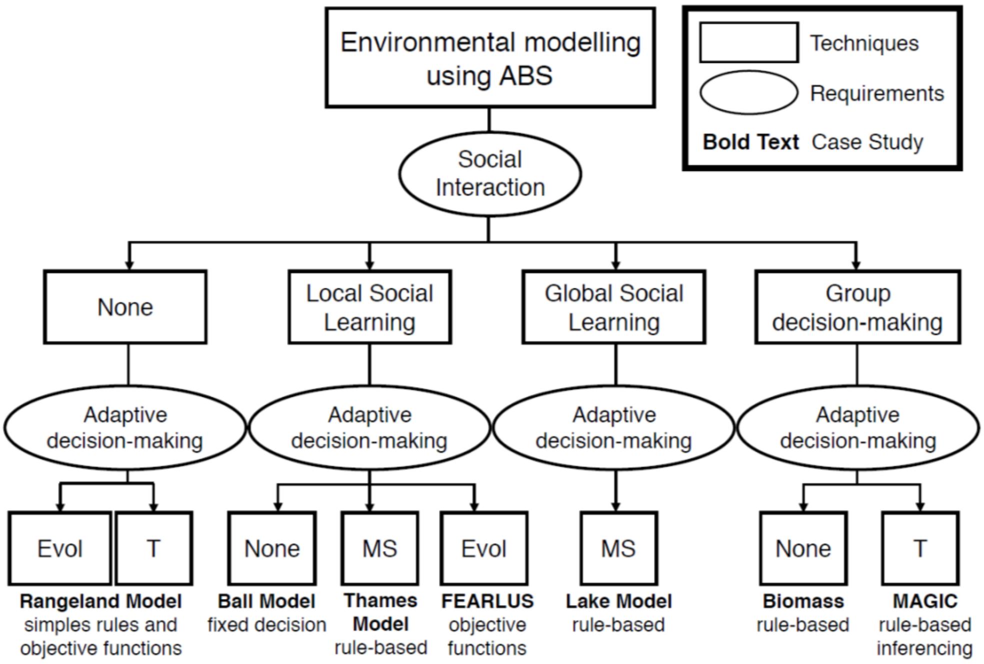


Figure 3.1 – Towards a taxonomy of ABS models in environmental management (Hare, 2010)

3.4 Using Serious Games in Emergency Scenarios

This section comprises a literature review on Serious Games and Virtual Reality environments as a complement to emergency training and education, namely fire drills.

3.4.1 Use of Serious Games for Evacuation Simulations

As mentioned before, games and simulators can be used for training. Imagine now a school, a services building, a shopping mall or any other highly populated environment, where fire drills are not taken seriously by occupants. If users were subjected to simulated scenarios, featuring characteristics of Serious Games, they would be expected to behave in a rather collaborative way, exposing their natural will to maximise their experience in the game (i.e. by gathering as many points as possible). Therefore, being repeatedly subjected to systems like that will very likely influence individual behaviour in longer term, resulting in quicker reactive responses whenever someone is facing a real emergency situation.

Figure 3.2 – Virtual fire dril environment (Smith and Trendholme, 2009)

The use of such tools could possibly save lives by training individuals with simulated scenarios towards the improvement of fire safety consciousness and enhancement of emergency plans. The emotion feelings that a game can provide are very realistic for the player (Kirriemuir & McFarlane, 2004).

This idea is not new. Situations that can hardly be reproduced due to their complexity and exceptionality can be simulated and SGs used to train people and test strategies. Nagel & Vermeulen (2010) proposed the use of a Serious Game for preparing a scenario of mass evacuation in the situation of a severe flooding. This has happened before in the Netherlands; a group of experts was formed to devise solutions to address that huge problem, helping the government to prepare contingency plans (Nagel and Vermeulen, 2010).

Smith & Trenholme (Smith and Trenholme, 2009) had a similar idea for fire drills. Their idea was to use games technology to create a virtual environment as realistic as possible, including fire and smoke effects and having the gamers trying to evacuate from the building (see Figure 3.2).

Figure 3.3 – SG for training occupants of a building in personal fire safety skills (Chitaro and Ranon, 2009)

A similar approach was proposed by (Chittaro and Ranon, 2009) aiming to train users and to educate them with fire safety skills. The former used the NeoAxis game engine, and 3D Studio Max to create the models to be rendered. To analyse players' movement and navigation a tool specifically developed by this research team was used (VU-Flow) using the logs produced by the players during game usage (Figure 3.3). These two examples were an inspiration for the research reported in this thesis. Unfortunately there have been no further developments to the research works presented.

3.4.2 Serious Games and Virtual Reality

Virtual Reality (VR) concept has emerged with the computers advent. One possible definition is the sense of being in an environment, generated by natural or mediated means, providing the subject a particular type of experience (Steuer, 1992). Frey used 3D virtual environments for psychological experimentations mixing VR and SG together (Frey et al., 2007). A step forward is to recreate virtual humans capable of interacting realistically with each other in a believable way (Guye-Vuilleme and Thalmann, 2000).

One early attempt was the OZ project at Carnegie Mellon University where a new agent architecture to implement some human behavioural characteristics, called Tok, was created (Bates et al., 1992). For improving the immersion sensations of users of VR environments, some complex apparatus were developed called CAVE; the acronym name derives from Cave Automatic Virtual Environment and consists of a theatre having projectors or screens in the walls of the room. There can be three or more walls-ceiling with images synthetically created (Cruz-N et al., 1993).

Figure 3.4 – VR Simulations in Evacuation Planning (Mól et al., 2008)

Other works referred in the previous section used VR for training and educating the player in fire safety (Chittaro and Ranon, 2009; Smith and Trenholme, 2009). An additional example in the fire safety domain more specifically for road tunnels, was developed and proposed by Max Kinateder, using Paul Pauli's company equipment, a VR driving simulator with Head Mounted Display (HMD) and VR-simulation custom-made software (Kinateder et al., 2012). Their experiment was aimed at demonstrating the existence of social influence on driver's behaviour in critical situations such as accidents in road tunnels. Yu & Ganz (Yu and Ganz, 2011) present the Mixed Reality Triage and Evacuation game "MiRTE" used in the development, testing and training of Mass Casualty Incident (MCI) information systems for first responders. Jorge et al. (2010) explored the SG concept related to emergency and evacuation simulations applied to complex industrial scenarios: power plants (Figure 3.4). They used the Unreal Engine to create a VR scenario for evacuation planning (Jorge et al., 2010; Mól et al., 2008).

DrillSim was developed by (Balasubramanian et al., 2006) using VR and Augmented Reality aimed to evaluate new techniques for crisis response; primary goal is to create an hybrid world that becomes an immersive training environment for first responders (Figure 3.5). Similarly Gamberini et al. (2003) built a Virtual Environment to study the participants' response to an unexpected fire emergency (Gamberini et al., 2003).

Some architects are using VR scenarios for the evaluation of their work. For instance (Yan et al., 2011) developed a 3D virtual environment using the BIM concept and Microsoft XNA framework to create a BIM-Game. The conversion from the architectural drawings made in standard de facto software tools such as AutoCad® and Revit®[10] (from Autodesk) is not a trivial accomplishment, although some work has been proposed so far (Yin et al., 2009).

[10] a product from Autodesk, Inc.

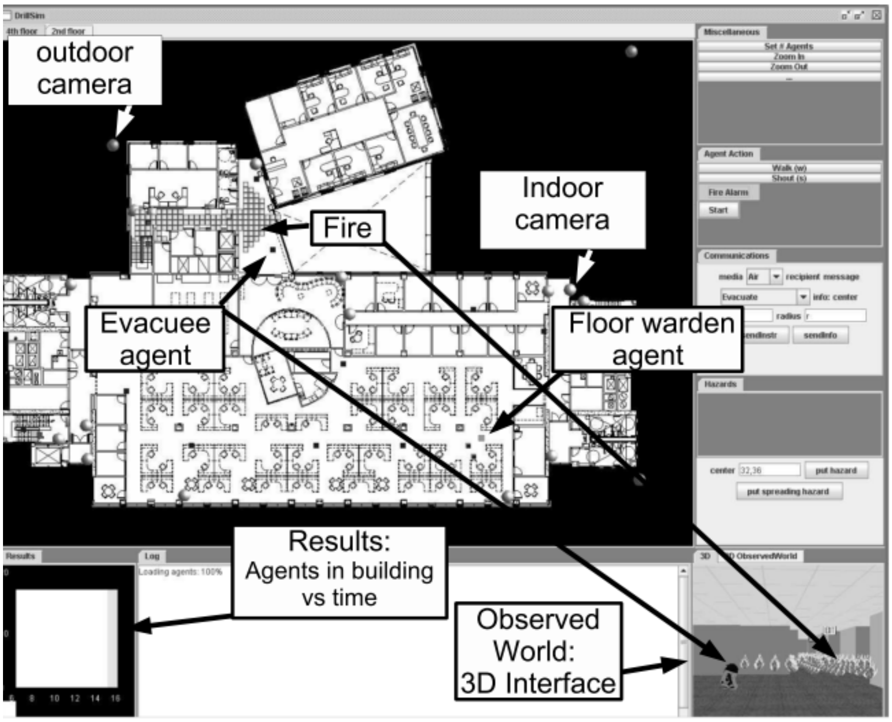


Figure 3.5 – Snapshot of DrillSim user interface (Balasubramanian et al., 2006)

One example mixing VR and SG was used by (Neto and Neto, 2012) to promote cultural heritage. In their example VR is exploited to recreate historical buildings; adding to this concept SGs such as quiz or questions & answers games, allowed to build an interesting educational tool to promote cultural heritage.

3.5 Human Behaviour Modelling and Simulation Using Serious Games

This section lists and illustrates the research found in the literature that uses SGs for modelling, and simulation of human behaviour when facing emergency situations.

3.5.1 Understanding Human Behaviour in Fire Situations

Margrethe Kobes' research for her PhD was largely based on psychonomics (Kobes, 2010). Psychonomics is an approach to psychology that aims to discover the laws that govern the workings of the mind. These laws lead to understanding how people process information. The primary concern of fire safety psychonomics is with the occupants' perception of the fire and the building environment.

According to Kobes (2010) the most crucial aspect of a building safety in the face of fire is to provide their occupants exits giving them the possibility of safe escape. The main concerns related to her country (Netherlands) were that the measures required by fire safety laws do not always provide the support that people in burning buildings need. A gap has arisen between fire safety policy and the technological as well as human aspects, which actually determine fire safety. Additionally, assumptions in Dutch policies were found to be inconsistent with the current scientific knowledge. Consequently, to bring fire safety measures into line with occupants' needs during an incident and understanding how individuals behave in the case of fire and fire evacuation were defined as essential goals.

The implementation of the psychonomic approach was made by using an assessment system based on fire safety engineering principles. Three scenarios were identified for this assessment system: the fire scenario, the fire repression scenario and the occupant response scenario. To predict a reasonable occupant response scenario, **new data are needed on evacuation behaviour in several surroundings and conditions**. In the case of fire evacuation, the ease of way finding (toward a fire exit) is very important for survival, as well as additional psychic stress caused by finding problems that might impair cognitive processes and the person's response. Kobes found little insight into how persons find their escape route and how this process of way finding can be supported with layout and design measures.

To collect new data on human behaviour in a fire, experimental research was conducted. A serious game approach for behavioural research was utilized as valuable supplement to the existing research methods. The final goal of this new research method was to be suitable to stipulate the necessary fire safety measures in designing a building based on psychonomics.

The goals of the research were, therefore, the following:

- To obtain insight into human behaviour in fires, particularly the intentions on which the route choice of evacuees is based.

- To study the influence of aspects of human factors, building factors and fire factors on the fire response performance, in particular the way finding performance.

Figure 3.6 shows Kobes' view on how fire response performance depends on human, building and fire features.

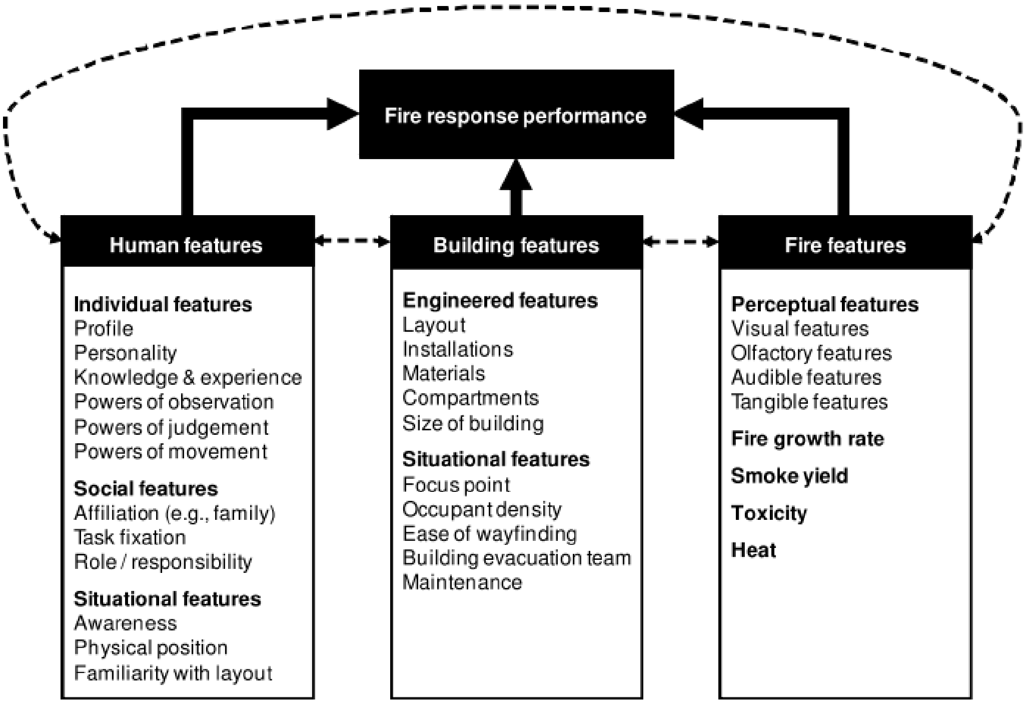


Figure 3.6 – Human, building and fire features influencing fire response (Kobes, 2010)

To implement the possibilities of virtual reality for studying human behaviour in fires in experimental research, the serious game 'ADMS-BART' was developed. This Behavioural Assessment and Research Tool (BART) is based upon a tried and tested simulation platform that is used by emergency training organisations all over the world since at least 1992 - the Advanced Disaster Management Simulator (ADMS) (Louka and Balducelli, 2001; Walker et al., 2011; Wright and Madey, 2008). The simulator is an interactive, real-time, physics-based virtual environment with realistic 3D visuals and audio, that recreates a realistic simulated environment. The simulator permits to do research on the behaviour of both individuals and groups. The projection takes place on a 2 by 2 meter sized flat projection screen. The movement of the virtual test person in ADMS-BART is controlled by using a joystick. Most of the trainees consider the training in a virtual environment to be as stressful as a real emergency response.

To make the software of ADMS suitable for behavioural research, it was extended with several functionalities, such as a tracking and registration device as well as a virtual replica of the Dutch Hotel Veluwemeer, used for the experiments carried out. This hotel was selected as the object of research on human behaviour in fires because: i) there are thousands of hotels in the Netherlands used by millions of individuals; ii) hotel accommodations present a high risk profile due to the fact that guests are not acquainted with the building layout, namely the exit routes; iii) many of the fatalities due to fire in the Netherlands occurred precisely in hotels during the night (Kobes et al., 2010c).

The new research method that uses serious gaming has been developed to obtain insight into evacuation behaviour and the effect of the building design on that evacuation behaviour, in particular on way finding. Moreover, to make sensible use of the new research method, it has been validated by comparing the results of the tests in the virtual hotel in the serious game ADMS-BART with results of the same kind of tests in the real hotel (Figure 3.7).

Figure 3.7 – Photos of fire exit in the real hotel (left) and virtual environment (right) (Kobes,2010a)

The experiments led to the conclusion that experimental research in the virtual setting of ADMS-BART was more convincing for participants than experimental research in a real-world setting, as some vital emotions, namely the sense of emergency, the sense of haste and the sense of stress, were significantly stronger in the tests in the virtual environment compared to the ones in the real environment. Additionally, there is no reason to assume that the behavioural levels in the virtual environment would be more optimistic than the behaviour levels in a real environment.

From her research, Kobes concluded that "*clear and extensive knowledge of human behaviour when faced with a fire is essential for the provision of the appropriate policy measures for a safe escape from it."* It was also noted that "h*owever, our current understanding of how people act during an incident is still very limited, especially when it comes to the psychonomics related to fire safety".* Her research gave evidence that *"we know how people behave, but we understand very little about what their motivations are for doing what they do."* In order to determine which safety measures should be taken to help people choose the right escape routes and which are the best practices and policies, it was pointed out that *"we need information about the perceptions, intentions and motives of those who are trying to escape from a fire. To realise adequate fire* *response performance, the definition of the fire safety of a building design should be based on psychonomics. Accordingly, further research is needed on building psychonomics in these circumstances"* (Kobes et al., 2010a).

From the works and conclusions made by the pioneering research by Kobes, further investigations are needed, and other methodologies must be envisaged in order to accomplish the noted situations and increase the safety level of buildings. The SG approach, however, proved to be a valid line of research and this path should be followed by further work. Her research was mainly focused on the analysis of existing safety measures in the Netherlands and validating such measures proposing some recommendations to the legislation of that country.

3.5.2 Predicting Human Behaviour in Emergencies

For predicting human behaviour in emergencies, Lawson proposed three different approaches using relatively modest resources: fire drills, virtual environments (VEs) and innovative talk-through approach in which participants describe the hypothetical actions they would take in an emergency scenario (Lawson, 2011). According with Lawson's findings, the talk-through approach is more suitable for use during the concept phase of a design as it is quick to implement and low resources are required; VEs and simulations will require detailed CAD models; finally fire drills whilst providing useful measures of human behaviour in evacuation scenarios, require a larger amount of resources, namely the building and persons availability.

He also developed a new approach based on experts predictions; while experts are involved in all of the other approaches, this one differs in that the primary information resource was the knowledge, experience and skill of the expert, rather than relying on interview responses, fire drills or simulations. The experts were nine fire officers with several years of experience. However findings have shown that the experts' predictions were not significantly correlated with the ones gathered from interviews with survivors of real domestic fires. The last approach consists in using scientific literature to investigate the predictive validity. So, in total five approaches were tested (see Table 3.4).

Table 3.4 shows a comparative performance analysis for five criteria for judging the quality of an approach: 1) validity 2) reliability 3) sensitivity 4) ethics 5) resources needed to perform the analysis. The presented comparison of approaches was achieved by applying the same standardised scenario consisting in evacuating the Psychology building at the University of Nottingham, where Lawson developed his research work.

Table 3.4 – Analysis of predictive approaches (adapted from table 9.1 - Lawson, 2011).

	Fire Drills	*Virtual Environment*	*Talk-through*	*Literature*	*Experts*
Validity	Good	Minor issues	Minor issues	Minor issues	Poor
Reliability	Good	Good	Good	Minor issues	--
Sensitivity	Minor issues	Good	Minor issues	Good	Poor
Ethics	Minor issues	Minor issues	Good	Good	Good
Resources	Minor issues	Minor issues	Good	Good	Minor issues

Results point in the direction of fire drills, virtual environments and talk-through approaches to have the best results. Validity of the approach is related to parameters selected by Lawson, namely the frequency and sequence of actions, time to evacuate, perception of danger, and exit choice. For this criterion, fire drills are considered by the author to be the best option, followed by the VEs. Experts' predictions were considered poor due to contradictions and difficulty in making predictions based on brief description of the scenario provided to them.

The research done by Lawson using the VEs approach went further than other similar works, also using the findings of a master student project who implemented a Second Life VE for evacuation drills. Yet results were much deceptive since evacuation times were different than in the real world. No further explanation for this was found. Perhaps some difficulties in using the computer interfaces could be the reason, as it happened in other examples (Ribeiro et al., 2012; Silva et al., 2013). Simulator sickness (Nichols and Patel, 2002) is a concern, and indeed, in this study, one participant reported having some symptoms. Nonetheless, the test group was relatively small (around 20 persons for each approach) and only one specific category of population: students in early 20's. This can hardly be seen as a significant sample of the population. Even in the University context there are teachers and other persons a lot older than 25 - the age of the oldest sample test user.

In brief, Lawson contribution was a systematic review of existing approaches for human behaviour prediction in emergency situations, with a critical comparison among them, shown in table 3.4. He also stated that talk-through and experts approach are recommended for early stages of building design whereas VE is more suited for mid and late stages of design onwards, when CAD blueprints become available. Fire drills are only possible when the building is functional and running.

The VE experiment was innovative in the way that a multi-player platform was used allowing to have up to four simultaneous players in the same simulation run. However some problems were reported, a few related with software and with the detailed modelling needed.

Future work reported includes running the aforementioned experiments in different building scenarios and even other types of emergencies. Also *a posterior* analysis could be valuable to validate the referred approaches and techniques. As far as the literature review suggested, no further developments or use of the appointed techniques and contributions of Lawson's work were made.

3.5.3 Other Examples of Serious Games for Studying Human Behaviour in Emergencies

Previously in Section 3.4, the use of SGs for evacuation simulations was discussed and some examples were presented. The recreation of fire drills using SG was proposed and tested by Smith & Trenholme (2009) and Chittaro & Ranon (2009).

Kolen *et al.*(2011) proposed using SG for training populations in the case of large-scale flooding, a real possibility in the Netherlands. Mass evacuation of cities is a critical event for which no plans can really be evaluated. One possibility is by using SG for helping planners, authorities and population in simulated events. The evacuation procedures and decision-making process must be rehearsed and evaluated for which a simulation tool is a valuable one to achieve a minimum level of experience among personnel in the rescue services. Nagel & Vermeulen (2010) say that computer simulations can be used for evaluating and testing mass evacuation plans. Their proposal is to use a flexible facilitation environment in which different games can be combined governed by a game control layer allowing the game controllers to manipulate the scenario aiming to maximize the learning effect for the participants (Nagel and Vermeulen, 2010).

What is missing in the aforementioned research is to record the participants options and commands during the game in order to elicit behavioural patterns that can lead to the inference of models of human behaviour in such events.

3.6 Research on Human Behaviour in Emergency Situations at LIACC

This section describes the on-going research at LIACC / FEUP in the past years related to pedestrian modelling, pedestrian data collection and serious games.

3.6.1 ModP Pedestrian Modelling

The ModP simulator's name comes from **P**edestrian **Mod**elling, initially developed by Aguiar Esteves for his Master Thesis, at LIACC/FEUP (Esteves, 2009). The goal was to create a tool for modelling pedestrians in multi-modal stations, allowing the optimisation of transhipments whilst accounting for factors such as space, modes of transport and pedestrian traffic flows, as well as the influence of all these parameters upon the decision making process of individuals using the station. Later, Fábio Aguiar adapted ModP to simulate and predict crowd behaviour during emergency and evacuation situations (Aguiar, 2010).

The simulator was developed in C++ with the Qt framework for interface, OpenSteer library for steering behaviours and OpenGL for the 3D visualization of the simulation. The simulator has four main modules: a graphic user interface, a 3D viewer, a simulation engine and a data analyser.

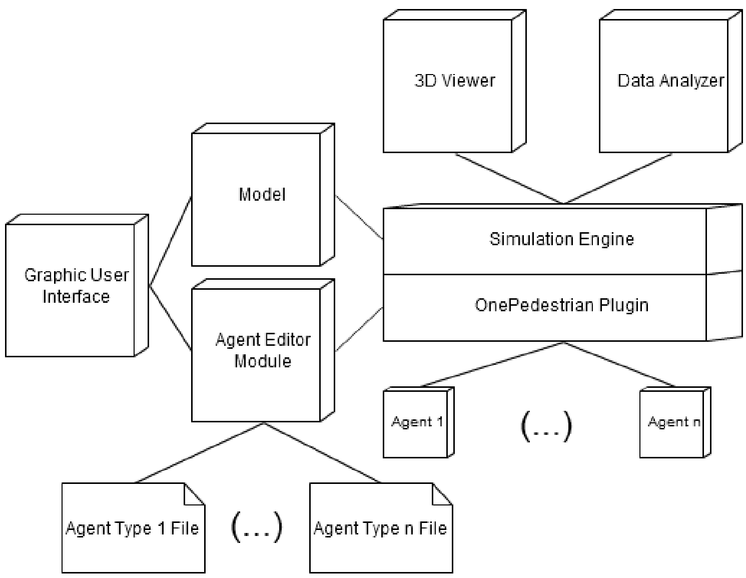


Figure 3.8 - ModP Architecture with the Agent Editor Module (Aguiar, 2010)

Aguiar expanded the original ModP with an Agent Editor Module (Figure 3.8) allowing the designers to simulate a broader range of crowds, creating the possibility to add new types of agents and configure the size of the crowd during the simulation. Also it was added the possibility of pre-defining a route for the agent (or agent type), for instance, the agent has to withdraw money from the ATM machine, pick some documents (train tickets) in a specific place, and buy a cup of coffee, before leaving the building (suppose it was a train station).

The Graphic User Interface (GUI) was enhanced to allow the setup of the various types of agents, the percentage of the total, and the frequency of their appearance, continuous, periodic or unique (Figure 3.8).

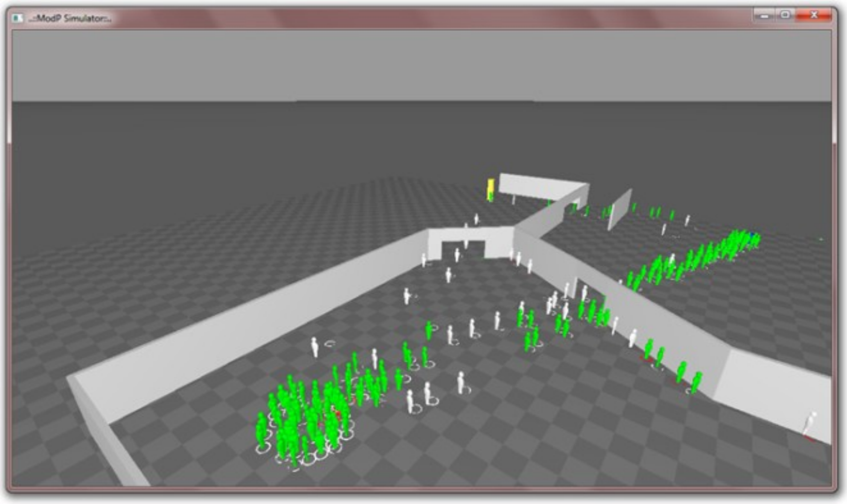


Figure 3.9 - Modp 3D viewer (Aguiar, 2010)

ModP presented a 3D viewer module and the results achieved were promising (Figure 3.9). This work has leveraged further research as it was inspirational for other master's students and this PhD thesis as well.

3.6.2 Using UWB for Human Trajectory Extraction

The Ubisense (http://www.ubisense.net/) real-time location system is an in-building ultra-wideband radio based tracking system which can obtain accurate information of the positions of people and objects. This system uses small devices (tags) that send UWB pulses to a network of hardware receivers fixated in the localization area, which use a combination of TDOA (Time-Difference of Arrival) and AOA (Angle of Arrival) techniques to estimate the position of each tag (Steggles and Gschwind, 2005). These tags can be attached to objects or carried by personnel. Sensors can also be connected to a computer, and Ubisense also provides a middleware platform which can manage and filter real-time location information and simplify the creation of location aware applications that monitor several localization areas simultaneously.

The system provided by Ubisense has seen wide adoption by the industry, especially in manufacturing plants, providing location services for tracking assets in order to improve and better control processes (Cadman, 2003). Lately, it has also been used to track personnel during military and fire fighter training and operations (O'Connor, 2005), and as a behaviour analysis tool based on coordinates of body tags (Luštrek et al., 2009).

These experiments follow a set of similar experiments performed in Germany at the Jülich Supercomputing Centre (Boltes et al., 2011; Seyfried et al., 2008, 2007, 2005), in which pedestrian trajectories were accurately extracted from video recordings. In contrast, in the described experiments automatic data collection is performed by assigning individual tags to participants, whose position was then tracked.

The aim for this research is twofold: i) to provide valid data for pedestrian dynamics model elicitation, as well as model validation in different facilities; ii) to evaluate the usage of a UWB based real-time location system for pedestrian movement data collection and trajectory extraction.

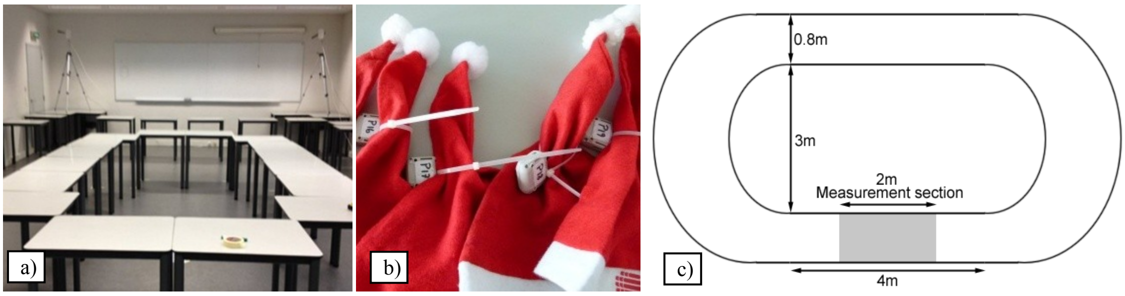


Figure 3.10: Experiment setup a) room and sensors b) Christmas hats with tags c) setup for the single-file scenario

Experiments were performed at FEUP room B227 (Figure 3.10), and were conducted with up to 30 participants, mostly students, whose average age was 21.4 ± 4.5 years and of mixed gender. Automatic data collection was performed by assigning individual tags to participants, whose position was then tracked. Four sensors were placed in the four vertices of the bounding rectangle containing the area where experiments took place (Figure 3.10a). For the purposes of these experiments, tags were attached on top of Christmas hats secured with straps (Figure 3.10b).

The experiments were divided in four general set-ups: single-file (Figure 3.10c), narrow passage and corner and T-junction (Figure 3.11). Each set-up was envisaged to provide data suitable to study different phenomena: fundamental relation in a simple scenario, unidirectional pedestrian flow through bottlenecks and more complex configurations like corners and merging of flows respectively.

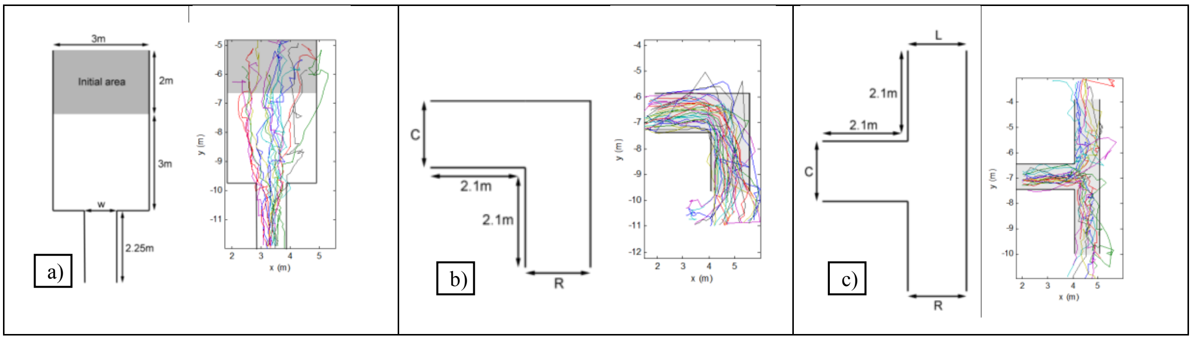


Figure 3.11: The other setups a) narrow passage; b) corner; c) T-junction.

UWB based systems have a great potential for pedestrian data collection and suitability for human trajectory extraction, presenting several advantages over traditional data collection techniques, expanding the breath of possible scenarios for experiments, such as situations of limited visibility for which data is inexistent. Compared with video recordings for tracking of people trajectories, UWB allows use in narrower spaces, lower ceilings and areas with line of sight restrictions. Other aspect is related with data collection. UWB based systems record the coordinates of position for each tag directly whereas video recordings must be later analysed and processed in order to extract positions/trajectories. Each tag carried by pedestrians is uniquely identifiable, allowing individual tracking thus enabling investigating both the dynamics of crowds and study the behaviour of specific individuals like child, elderly or people with mobility impairments.

On the down side, it has a lower sample rate than video: about 5 Hz in the case of UWB versus 25 Hz with video. Also, video techniques present synchronized results whilst UWB does not. Moreover, technical limitations such as lack of fine spatial precision make it not optimal for extracting microscopic properties of traffic, such as velocities and densities at a disaggregated level.

In conclusion, and when comparing the drawbacks with the advantages, UWB techniques for human trajectory extraction seems a viable approach. It is particularly suitable for scenarios where video is less applicable and pedestrian fine positioning is not an issue, such as for macroscopic analysis: e.g. egress time, path choice and behaviour scrutiny (Vasconcelos et al., 2012).

3.6.3 LIACC Serious Games and EVA

Ribeiro (2012) developed a new approach to the ModP using the Unity3D®[11] software game engine to overcome the need of having to code all graphical details. Game engines provide rapid

[11] Software developed by Unity Technologies

prototyping tools and solve all the physics and rendering issues. The new version was coined ModP3D although development was made from scratch and in a different paradigm, to keep the continuity and show that this evolves directly from the work of his predecessors at LIACC. The scenario used was the building where LIACC is based at FEUP campus (Figure 3.12). A 3D model developed using Blender was imported to the Unity3D game and some users tested the virtual evacuation fire drill developed.

The model had some sound and image features that were added to increase the immersion sensations to the player. The fire alarm sound used was the same that is used by the automatic fire detection system at FEUP. Smoke and flames were also added spreading as time goes by. It was also implemented the possibility of generating NPC (Non-Playing Characters). There NPC had a starting point and a vanishing one.

Results were very interesting and presentations in conferences gave good feedback (Ribeiro et al., 2012b; Ribeiro, 2012). Users' feedback was also positive although some players stated their difficulty to use the keyboard/mouse combination to steer their Avatar, especially those without previous gaming experience.

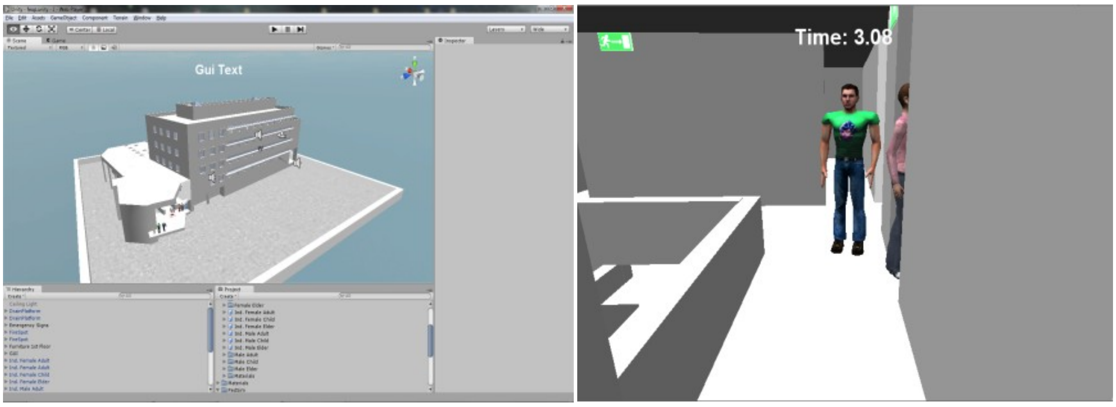


Figure 3.12 – Using SG to train evacuation behaviour (Ribeiro et al., 2012a)

Silva (2013) continued the previous work this time using a new scenario. A large three-floor building, was imported from Autodesk's Revit and some furniture was added to give a more realistic, almost photo-quality, ambient (Figure 3.13). Then, a character using the First Person Shooter (FPS) was created. The building was adapted to look like a hospital. The SG prototype developed using Unity3D was coined EVA. This name derives from the three initial letters of EVAcuation. It also relates with the first woman known, Eve (that is *Eva* in Latin languages, such as in Portuguese). This name was chosen to stress the originality and pioneering approach to use SGs for training emergency procedures in healthcare environments.

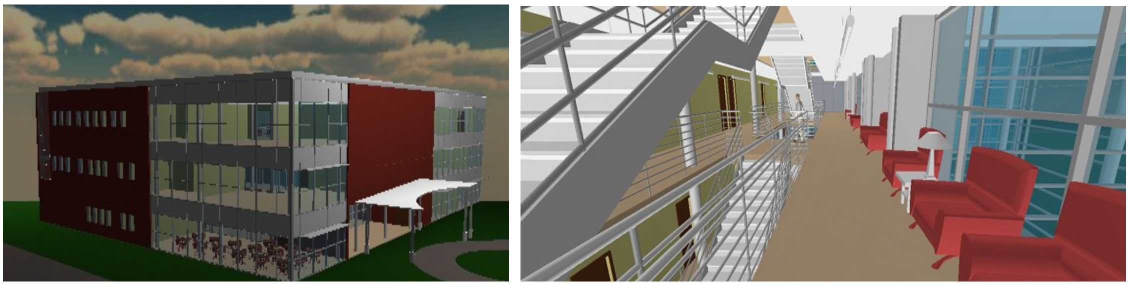


Figure 3.13 – EVA building exterior and inside view (Silva, 2013)

To test the previously described prototype, some volunteers were invited to play the game. A total of 20 individuals participated in the experiment playing the EVA SG (Figure 3.14).

Some of the subjects were medicine students, quite used to the stressful environments of hospitals. There were also three nurses. For this particular group, this tool has an increased importance because they are aware of the typical daily reality at hospitals and can easily realise the problems arising should such an event, such as fire alarm, occurs.

Figure 3.14 – Some EVA screenshots of the SG (Silva, 2013)

Silva expanded the use of EVA as FPS videogame where the player has to steer her Avatar towards the exit, and included a simulator based on the Peer Design Agent (PDA) approach. Using data recorded from the players that played the EVA game, a character reproducing the players' choices was created (Figure 3.15). This concept is called PDA, because the virtual agent behaviour is based on the data acquired by the sum of all gamers that played EVA.

Figure 3.15 – EVA as a Simulator using PDA concept (Silva, 2013)

Silva expanded the use of EVA as FPS videogame where the player has to steer her Avatar towards the exit, and included a simulator based on the Peer Design Agent (PDA) approach. Using data recorded from the players that played the EVA game, a character reproducing the players' choices was created (Figure 3.15). This concept is called PDA, because the virtual agent behaviour is based on the data acquired by the sum of all gamers that played EVA.

3.7 Summary

The literature review and the related works, presented in the previous sections, identify some gaps to be tackled by the research.

This Chapter starts by presenting a deep analysis of evacuation simulators. Among them, ModP, the pedestrian simulator developed at LIACC, is characterized according to the taxonomies presented in Section 3.2, a serious formalization research towards the features that an ideal evacuation simulator must have. The tables comparing existing evacuation simulators show that data used by them has a significant impact on the validation of the models towards their acceptance by both the scientific community and practitioners. In conclusion, the main drawback regarding evacuation simulators is the lack of sufficient and credible data, particularly concerning human behaviour.

The need of defining taxonomy for the interactions between the avatars, environment, objects and even other intelligent agents within the context of virtual reality worlds, which includes VE used in the development of SGs, is described in Section 3.3. Some examples in relation to this aspect are presented. However, this is a field of on-going research for which no definitive taxonomy was found during the present research, because each application or research group uses their own approach.

Sections 3.4 (using SGs in emergency scenarios) and 3.5 (human behaviour modelling and simulation using SGs) introduces a few examples of using SGs for training and the elicitation of human behaviour with the aim of using that knowledge for modelling and simulation. All research work presented has in common the fact that they had no follow up. The pioneering research by Kobes, using SG as a means to investigate and train human behaviour during evacuation scenarios, proved this technique to be a valid line of research. Her research, however, was mainly focused on the analysis of existing safety measures in the Netherlands and proposing some recommendations to the legislation of that country. She concluded that further research is needed particularly regarding "*the perceptions, intentions and motives of those who are trying to escape from a fire"* - precisely the application domain of the present thesis. Another important research work reported, from Lawson, is a systematic review of existing approaches for human behaviour prediction in emergency situations. Some preliminary experiments were attempted using VE. Lawson identified as future work the need of running more experiments in different building scenarios and other types of emergencies. Also *a posterior* analysis is proposed to validate the referred approaches and techniques. The need of recording participants' options and commands during the game in order to elicit behavioural patterns was mentioned by Nagel and Vermeulen's research. These aspects were inspirational for the present thesis.

Finally at Section 3.6 the Portuguese contribution for better understanding the human behaviour in emergency situations is described, together with the research made at LIACC in recent years, boosted by the collaboration with LNEC. Early developments started with ModP the multi-modal pedestrian simulator. This inspirational work presented some drawbacks, namely, the need of all scenarios to be made using its built-in scene designer. ModP lacks the possibility of importing 3D scenarios from existing blueprints, made using AutoCAD®[12] software, limiting its use. Instead, using Unity3D games, it is possible to recreate vivid 3D realistic scenarios without much effort, thriving the development of EVA the EVAcuation simulator, ultimately leading to the development of SPEED.

Human behaviour at the lower level can be elicited by the use of technologies such as Ubisense. Indeed, some interesting experiments were carried out, which are detailed thoroughly in Section

[12] a product from Autodesk, Inc.

3.6.2. These techniques for human trajectory extraction can lead to better understanding decisions of pedestrians made at the lowest level, during their way.

In conclusion, relevant research is presented in respect to the evacuation of buildings in emergency situations using VEs and SGs. However, this field is still on its infancy. Kobes developed the SG ADMS-BART using military technology, a means hardly available outside the Netherlands civil protection. Nonetheless, she concluded that understanding how people act during an incident is important, and more extensive knowledge of human behaviour is needed. On the other hand, Lawson's research points in the direction of using VEs to implement fire drills, yet results were deceptive, having experienced some problems related with software and with the detailed modelling needed. With regards to the research at LIACC, it follows up initial attempts to improve behavioural modelling formalising a thorough methodology for the elicitation and modelling of humans when acting as pedestrians. Therefore, a gap analysis resulting from the previous conclusions points to the need of developing new methodologies aimed towards the elicitation of human behaviour, which the present thesis plans to accomplish.

4. Methodological Approach: Method & Materials

4.1 Overview

This chapter presents the core of this thesis, a methodological approach leading to the Conceptualisation of a novel methodology for human behaviour elicitation, coined SPEED, the Conceptualisation experiment designs and their corroboration by the international expert panel using the Delphi process. This is followed by the description of some preliminary experiments towards the implementation of serious games, to test its practicability and the challenges posed by the development of digital videogames.

4.2 SPEED: Simulation of Pedestrians and Elicitation of their Emergent Dynamics

The problem of modelling and simulating pedestrians much resides in the need for further knowledge on human behaviour to better understand of pedestrian dynamics and interactions, and of all aspects associated with their movement. A full understanding of crowd behaviour would require exposing real people to the specific environment for obtaining empirical data, which is difficult since such environments are often dangerous in nature. In addition to studying crowd behaviour based on observations and historical records, computer simulation is a useful alternative that can provide valuable information to evaluate a design, to help the planning process, and for dealing with emergencies.

To address the lack of behavioural data and the need for new elicitation methods of data acquisition and behaviour modelling techniques, identified in Chapter 1, a novel methodology for human behaviour elicitation conceived is coined: **"Simulation of Pedestrian and Elicitation of their Emergent Dynamics"**, SPEED.

To reveal the human behaviour and try to capture the complex and uncertain activities of pedestrians in the real world, it is devised a first-class abstraction for behaviour elicitation (see Figure 4.1), using:

a) agent-based simulators;
b) high-fidelity simulation;
c) serious games;
d) the real world.

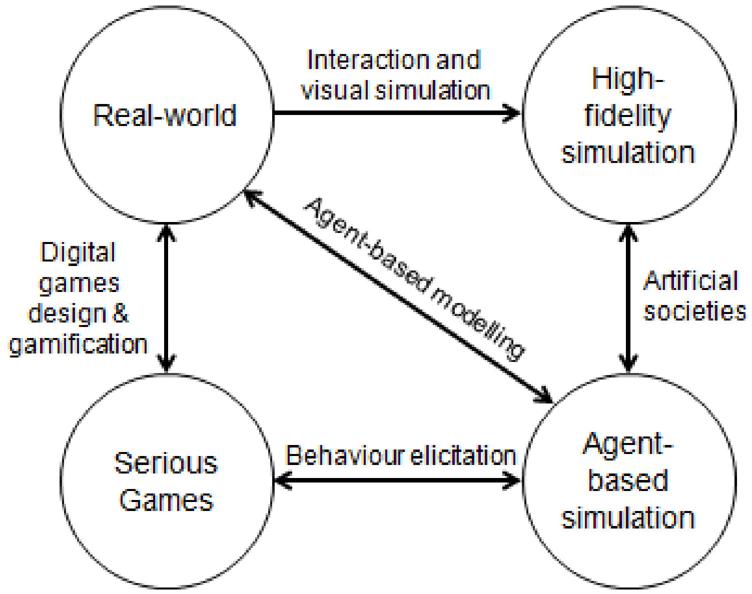


Figure 4.1- The methodological perspective of SPEED (Rossetti et al., 2013)

The real world ecosystem is where pedestrians live and interact. The identification of a real-world ecosystem follows the same abstraction as presented by (Rossetti et al., 2011, 2007). According to this view, real urban buildings and pedestrians are seen as a common environment where physical components and actors such as safety systems (including signs, fire detection and alarm systems) and the evacuees "live" and interact. The observation of pedestrians' behaviour has been traditionally performed through surveys/questionnaires, video-streaming cameras and other type of sensors, such as RFID tags (Vasconcelos et al., 2012). From the observations in the real-world ecosystem, scientists, practitioners, and decision-makers build abstraction models and analytical tools with diverse purposes. Each of such tools can also be considered ecosystems in the same abstraction dimension.

For practitioners and stakeholders simulating extreme situations, testing theories and what-if scenarios using agent-based simulation (ABS) is of paramount importance. The ABS ecosystem is actually where artificial societies (as a means to represent human behaviours and their social interactions) grow and breed. To create such virtual worlds the modelling of agents by means of ABS needs behaviour knowledge for which behaviour elicitation is required.

Through rich graphics with high degree of detail and virtual-reality techniques allowing countless interaction forms, the high-fidelity simulation ecosystem recreates the real domain. While trying to preserve the same level of immersion, high fidelity simulations allow other facets of the system to be observed on a controllable basis, which would not be possible through experimentation with the real system, though. Different psychological experiments are carried out in such simulation environments, such as those using driving simulators and similar environments. Insightful analysis of intrinsic decisional mechanisms of subjects, either individually or in groups, may be performed with relatively high accuracy. However, such sort of simulators is built on very complex and expensive infrastructures, and gathering subjects to participate in the experiments is another issue that may limit the scope of the studies.

Instead of using high-fidelity simulation that recreates with a high degree of detail the real domain, as used by (Kobes, 2010) for which complex and expensive simulators are necessary, such as VR-based Cave Automatic Virtual Environment (CAVE) and other sophisticated virtual-reality technology (Cruz-N et al., 1993; Kinateder et al., 2014) SPEED uses SGs for behaviour elicitation. The aim is to complement rather than to replace other efforts and technologies, using SGs techniques to enhance behaviour modelling and analysis (Almeida et al., 2014c).

This extended account of the SG concept is in accordance with the integrative perspective of behaviour elicitation to reveal the decision processes behind the course of actions people perform to achieve certain goals and respond to stimuli, or during deliberation. This process is not just a matter of collecting data through logs of different and successive interactions of the player during the game for post processing. Rather, it makes use of the intrinsic nature of SG to impel the player to add semantics to every decision and action performed during the game that might better clarify the sequence of cognitive states that resulted in or triggered certain actions. In other words, it is the player that will model his/her own agent, in a process that has been defined as peer-designed agents (PDA) (J. S. V. Goncalves et al., 2014; Lin et al., 2010; Talman et al., 2005). Briefly, serious games were integrated into the conceptual framework SPEED by combining behaviour elicitation with the PDAs, allowing players to feature their peer agents with their own idiosyncrasies (Rossetti et al., 2013).

This concept consists on the preliminary step towards the implementation of SPEED. The SPEED platform borrows concepts used in the specification of the MAS-Ter Lab framework (Ferreira et al., 2008; Passos et al., 2011; Rossetti and Bampi, 1999; Timóteo et al., 2010). The MAS-Ter Lab is based on Artificial Transportation Systems (Rossetti and Liu, 2015). The fundamentals of the SPEED framework were described elsewhere (Rossetti et al., 2013). The SPEED framework has a wider perspective, having other examples of applications of this concept (Alves et al., 2013; Gonçalves et al., 2012, 2015; Macedo et al., 2013; Pereira and Rossetti, 2012).

The behaviour elicitation methodological approach is the core of the SPEED framework that integrates agent-based modelling, social simulation, and Serious Games. SGs can be used both as a training tool and an important observation aid (Ribeiro et al., 2012a; J. F. Silva et al., 2013). The knowledge acquired with the behaviour elicitation is to be applied with the peer-designed agents (PDAs) that will populate a synthetic population for evacuation simulators, the final goal of SPEED, consisting of a powerful tool for behaviour elicitation (Rossetti et al., 2013).

4.3 Towards the Implementation of SPEED

During the development of the methodological approach underlying the SPEED framework, three main phases to be implemented are identified. The first one consists in collecting data related to the phenomena to be observed. The traditional methods use direct observation, in real time or by later analysing films and photographs. Another recurrent way is by means of questionnaires. The novelty of the SPEED approach consists in using digital games to generate virtual worlds in which players can experience an immersive environment and thus recreate typical scenarios from which behaviours can be elicited.

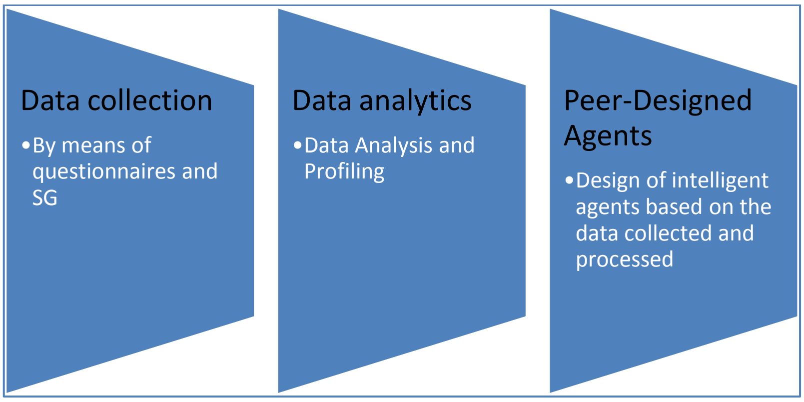


Figure 4.2 - Diagram of the SPEED three main processes

Afterwards, the data collected needs to be analysed in order to synthesize the knowledge gathered. The importance of this phase resides on the need to represent a population, with a reasonable degree of accuracy, but without having to characterize each individual. For such it is necessary to have a certain number of behavioural profiles in which all subjects might fall.

The last phase consists in using the elicited data to grow and breed a synthetic population of pedestrians interacting in a virtual world, producing phenomena that observing experts can use for their experiments. The design of the intelligent agents and the characterization of their reasoning features is the basis for the concept known as peer-designed agents.

In synthesis, the implementation of the SPEED framework consist of the following three main phases (see Figure 4.2):

i) data collection;
ii) data analysis;
iii) peer-designed agents.

Essentially, the first phase consists in setting up experimental setups, using questionnaires and SGs for data collection. Then, appropriate data analytic techniques are necessary for identifying typical behaviours and thus creating profiles. At last, results will be used for the modelling of intelligent agents based on the data collected.

To deliver this strategy the methodological approach envisaged can be summarised by the following steps:

a) To design a set of scenarios that are typically present in building evacuations;
b) To specify the requirements of SG and implement a prototype;
c) To align the type of questions in the questionnaire study with scenarios in the SG prototype;
d) To carry out Expert Panel corroboration (based on the Delphi method);
e) To carry out a pilot study for co-validation of the questionnaire and the SG using statistical tests as well as experts in the field;
f) To carry out final tests using previous data to enhance both the questionnaire and the SG for data collection and analysis.

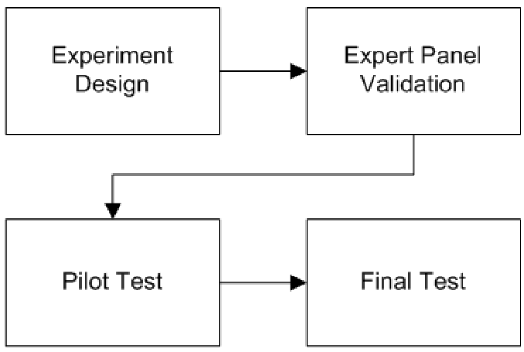


Figure 4.3 – SPEED process flowchart

The flowchart shown in Figure 4.3 summarizes the sequential tasks that were accomplished. Basically, the steps are:

1) To conceive the experiments;
2) To submit for validation by an expert panel;
3) To implement a pilot test;
4) To run the final tests taking into account the knowledge gathered in the previous steps.

The design of the experiments poses challenges at different levels: the Conceptualisation, the context and the implementation. When imagining the scenarios in which the experiments are made, the goals to achieve with them are the primary concern. The context in which they occur is another important aspect closely related to implementation issues, due to technology limitations or the inherent complexity associated. The output of this task consists of the SG requirements.

Selecting the appropriate game engine to be used on the development of the SG that meets the requirements and implement a prototype, as a proof of concept is the following task.

Then, for each scenario with the corresponding environment, set of goals and implementation details, a questionnaire must be prepared. The questions must be aligned with the game scenario for allowing the subsequent analysis.

Afterwards, the scenarios with the matching questionnaire and SG shall be evaluated by an international expert panel, with proven experience in the fields related to the experimental setup, namely fire safety, building evacuations and human behaviour. For this task, the Delphi method is used.

At last, the experiences must be carried out, but only after a pilot test has been performed, so as to evaluate the methodology and introduce the necessary improvements, if needed.

4.4 Conceptualisation

This section details the steps that were put up to deliver the methodological approach described earlier on namely the experiments design phase, the questionnaire and game scenarios Conceptualisation and the validation process.

4.4.1 Designing the Experiments

The experiment design phase is arguably one of paramount importance, and as such, essential for launching the foundations of all methodological processes. Therefore, to help steering the construction of the questionnaire and the experimental setup, the following steps are identified:

1) List all possible variables that might be assessed using the questionnaire as well as the SG;
2) Specify the questions to measure each variable identified in the previous step;
3) Specify the initial version of questions for the questionnaire and the SG;
4) Think about the nature of questions and type of hypothesis to be tested (e.g. differences between groups; relations between variables for establishing associations);
5) For each hypothesis select the appropriate statistical technique considering the expected results;
6) Decide the expected answer for each question.

For the experiments to be implemented using the SG concept, they must follow closely the questionnaire, even though exploring the advantages of the computer graphics and animation features present in digital videogames.

4.4.2 Acquiring Variables and Data

The very first step was to identify variables and data to be acquired from both the questionnaires and the SG. The variables that were identified and selected as essentials to be assessed through the use of questionnaires as well as using the SG include the following:

- Subject characterization: age, gender; dominant hand;
- Fire knowledge (education/training);
- Education level (basic, high school, university);
- Computer expertise;
- Videogames expertise.

The data to be acquired from both the questionnaires and the SG:

- Tendency to turn right / or left at corridor intersections;
- Tendency to follow emergency signalling;
- Tendency to take risks in emergency situations (go through smoke or go the other way);

- Tendency to trust & follow people (follow others test);
- Tendency to behave erratically (or change their minds: different answers at the same situations);
- Tendency to use the shortest exit or prefer the normal way.

The psychological profile of subjects is considered by some authors to be an important aspect that must be taken into account when assessing their behaviour (Klingsch et al., 2010; Kobes et al., 2010b; Kuligowski and Peacock, 2005; Larios, 2012; Mu et al., 2013). For this purpose a psychological test was considered, namely the 16 PF-5 (Cattell and Mead, 2008)[13]. The aim is to find if there is any association between the psychological dimensions and the tendencies that were identified, such as turning left or right at intersections or following others.

4.4.3 Designing the Scenarios

Subsequently, the next step consisted of the design of several experiments recreating scenarios that are typically present in building evacuations. Based on literature and opinions from experts a set of scenarios was identified. One of the great advantages of this methodology is that it imposes no limit to the number of scenarios that can be used; imagination and the ability to conceive and implement the questionnaires and SGs are the solely requirement.

To this point, four experiments were devised:

1. Alarm Id;
2. Alarm reaction;
3. Exit Choice (from single room);
4. Auditorium.

The 1st experiment aim is to test if subjects can identify, among various sounds, which is the fire alarm. This aspect is very important in real situations, because it has been noticed that many times the occupants of a building, during an emergency situation, ignore the alarm sirens (Pigott, 1989). Modern cities have many different alarm sounds, besides fire there are all sorts of other alarms (gas leak, high carbon monoxide levels, and intruder alarms). In the absence of standardised alarms, this test is expected to reveal the common people knowledge and ability to correctly identify fire alarms and distinguish them from all others (Subramaniam, 2004).

[13] Since these tests are available only for certified psychologists, it was required the help of a Psychologist (Drª Liliana Mendes) who bought a set of tests, properly validated and calibrated for the Portuguese population, from the company having the licence to distribute them in Portugal, Cegoc (see http://www.cegoc.pt/).

The 2nd experiment intent is to compare the answers to the questionnaires made by Cordeiro (Cordeiro et al., 2011a) and assess which are the tasks that subjects perform after hearing a fire alarm. The goal of this experiment is to identify and prioritize the pre-evacuation actions, an important aspect for fire safety engineers (Gwynne et al., 2003; Horasan and Bruck, 1994) .

The 3rd experiment purpose consists in testing the tendency to turn left or right at intersections, when leaving a room without any indication. This same scenario is used as well to test the tendency to follow emergency signalling, to take risks in emergency situations (go through smoke or turn away from it), to trust & follow people (follow-other test) and to behave erratically (or change their minds, i.e., having different answers to similar situations). This is called the "exit-choice" scenario (Kobes et al., 2010d). Although several experimental setups are known, the scenario envisaged here is a novel one considering the dimensions and aspects to study (Heliövaara et al., 2012; Lo et al., 2006; Nilsson, 2009; Shendarkar et al., 2008; Takahashi, 1989; Xie, 2011; Zacharias, 2001).

The last experiment target is testing the tendency to use the shortest exit or prefer the normal way out and if the exit choice in an auditorium depends on the row, or room level, where the subject is seated (Nilsson and Johansson, 2009). The auditorium scenario is cited in the literature, but no experimental setup using virtual reality seems to have been effectively investigated as of yet, to the best of the research for this work (Forell et al., 2012; Kimura and Sime, 1989; Klingsch et al., 2010; Toyama et al., 2006).

4.4.4 Aligning Serious Games with Questionnaires

For each experiment, there is a set of questions and the correspondent SG sequence and challenges to the player aligned with the questionnaire, to allow for the comparison of results and thus the co-validation process.

The fine tuning iterative process was made with the help of field experts who suggested the proper metrics and variables to be measured, as well as the questions to be asked, and the expected answers to the questionnaire. This process consisted in asking some of the experts their opinion, during the setup and preparation of the questionnaire. Therefore, the version presented to the expert panel for their evaluation comprises prior consulting.

Afterwards, the last step was to align the questionnaire with the SG. The SG should have the same game sequence and challenges to the player aligned with the questionnaire to permit the comparison of results and thus the co-validation process.

4.4.5 Co-validation of Questionnaires and Serious Games

The co-validation process consists in comparing the results obtained from both the questionnaire and SG and by using the appropriate statistical techniques to assess if these elicitation methods are comparable. To exclude biasing data and contamination of results, for each scenario, two groups of volunteers are selected. The first group has to answer the questionnaire and later play the SG. The second group does the same but in reverse order, first plays the game and later answers the questionnaire, thus acting as control group. This methodology was devised for the results analysis and to perform the statistical co-validation.

In order to observe the association between the results from the game and the ones from the questionnaire, the null hypothesis (H_0) refers to an extreme situation when there is no relationship between the two phenomena of the study. Rejecting or disproving the null hypothesis—and thus concluding that there are grounds for believing that there is a relationship between two phenomena is a central task in the modern practice of science, and gives a precise sense in which a claim is capable of being proven false (Agresti, 2002).

A significance level of 0.05 will be used for the statistical evidence. The significant level (alpha α) is the threshold of a pre-chosen calculated probability (p-value) for which the null hypothesis is true. This value is typically set to 5% (Vaughan, 2013). When $\alpha = 0.05$, this means that if the p-value is less than 5% ($p\text{-value} < \alpha$ or $p\text{-value} < 0.05$) then the null hypothesis can be rejected and therefore the hypothesis has a statistical significance level thus reflecting the characteristics of the population sample. Otherwise, when the p-value is greater than the significant level ($p\text{-value} > \alpha$) this means that the null hypothesis cannot be rejected and therefore no conclusions can be inferred from the study (Agresti, 2002). Statistical hypothesis tests making use of p-values are commonly used in many fields of science and social sciences.

The Pearson's chi-square test (χ^2) is used to observe the association between the game and the questionnaire, to determine whether there is a significant difference between the expected frequencies and the observed frequencies in one or more categories. When the $p\text{-value} < \alpha$, this means that there is a statistical evidence of association. To reduce the error in approximation for discrete probability values, a continuous chi-square distribution is used (when indicated in the legend of the results).

Whenever the chi-square test shows no conclusive results, the Fisher's test is used instead. The Fisher's exact test is a statistical significant test used for categorical data in the analysis of 2x2 contingency tables, particularly when the samples sizes are small. The smaller the p-value resulting from the test, the greater the evidence for rejecting the null hypothesis, showing that there is a statistical evidence of association.

To evaluate the differences between the individuals' options in the game and answers in the questionnaire the McNemar's test is the one that suits best for 2x2 tables with pairing (McNemar, 1947). Whenever the p-values are lower than the significant level ($\alpha = 0.05$) this means that there is no statistical evidence of association. A variant test is the binomial sign test giving an exact p-value for the McNemar’s test.

For the results analyses the Statistical Package for the Social Sciences (SPSS), which consists of predictive analytical tools for multivariate data, will be used in combination with Microsoft Excel spreadsheet.

Later on, during the test pilot, the validity of this methodology is checked and a verification and calibration of the questionnaires and SGs performed. Questions could then be rephrased and the scenarios in the game might also suffer some tuning. But, before this, the overall experimental setup was put up to an expert panel for validation, using the “Delphi process” (Brown, 1968).

4.5 Expert Panel and the Delphi Method

During the whole process of designing the methodology and conceiving the scenarios, some experts on the field of fire safety and more specifically buildings’ evacuation were consulted. This was the genesis for the idea of using a more robust and sound method for doing this systematically, the Delphi method or process briefly described earlier in section 2.6.1.

4.5.1 Methodology

The Delphi method is a systematic interactive forecasting method which relies on a panel of experts (Brown, 1968). The method consists on having the experts answering questionnaires in two or more rounds, until the group converges towards the final version, based on the principle that the opinions from a structured group of individuals are more accurate than those from unstructured groups (Rowe and Wright, 1999). The overall idea is that the best approach or solution for the problem under discussion emerges from the panel of experts. This method is used in a variety of applications, from forecasting to policy-making, including areas such as marketing, technology and science, to predict new trends and research directions. The technique can be adapted according to the final expectations of its use with several Delphi like approaches.

The elicitation method used was based in the work of (Rowe and Wright, 2001) that suggests using a group of no more than 20 experts, from heterogeneous backgrounds, use the mean or median estimate of the panel plus the rationales from all panellists to measure the level of consensus, and do as many rounds as needed to reach an agreement.

Based on the aforementioned method, the following steps were devised:

- Select the expert panel group;
- Prepare the questionnaire;
- Submit the questionnaire and collect responses;
- Analyse responses;
- A new round until consensus is reached.

The initial version of the questionnaire was developed while contacting the experts to be part of the expert panel. A preliminary round was made during this phase. These expert's comments on the initial version of the questionnaire as well as on the SG scenarios devised were of the upmost importance for having an initial version very close to the final questionnaire. This fine tuning was an iterative process with the experts who gave their insights into and suggestions on the proper metrics and variables to be observed, the questions to be asked, and the expected answers for each question. Their remarks were the basis of the experimental setup for the pilot test, and later for the final test. The aim of using this methodology was to ensure the least possible number of rounds to reach a consensus.

4.5.2 Expert Panel Questionnaire

The questionnaire has four sections (see Table 4.1): I - subject characterization; II – knowledge on fire safety; III – psychological aspects; IV – Scenarios (questionnaire versus Serious Game).

Section one comprises typical subject aspects, such as age, gender, education and profession. Computer expertise (or computer basic skills) was included to avoid bias at results due to lack of technological ability with computers. Same with the "games expertise" question. The dominant hand is an aspect that might have some influence on the exit-choice scenario, to which more research is needed since there is no current knowledge on this aspect.

Section two aims to categorize the subject knowledge on fire safety: if he/she has any sort of fire training education (for instance, attended a seminar or a course on fire safety), in which areas (general fire safety, extinguishing procedures, evacuation procedures), periodicity of such training (annually, twice a year, one time only). Another set of questions in this section is related to possible fire-related experience: where, what happened, the reaction to the fire and if the activity that was undergoing at the time of the incident had any influence on the reaction.

Section III is just presented to inform the expert panel that the 16PF-5 psychological test (Cattell and Mead, 2008) aims to assess if there is any association between the behaviours and psychological dimensions.

Table 4.1 - Questionnaire sections

Section	Items
I - subject characterization	Age Gender Dominant Hand Education Profession Computer expertise Games expertise
II – knowledge on fire safety	Fire Training (FT) FT areas FT periodicity fire-related experience where? what? behaviour activity influence
III – psychological aspects	16PF-5 test
IV – Experiments	Alarm Id Alarm reaction Exit Choice (from single room) Auditorium

Section IV contains the experiments and the correspondent questionnaire and SG for each.

All questions presented to experts had to be evaluated using the typical five-level Likert-type scale[14]:

1. Strongly disagree
2. Disagree
3. Neither agree nor disagree
4. Agree
5. Strongly agree.

It was also provided a “comments” box for each question; this space should be used either for comments or rephrasing the question. The complete questionnaire is presented in Appendix A.

4.5.3 Expert Panel Selection

A total of invited 22 experts were contacted, either by e-mail or telephone, for live interviews and filling up a questionnaire. The group sample is heterogeneous, but having some kind of fire safety in common. Professional experience includes fire-fighters, fire commanders, fire safety engineers, experts from the fire safety industry (from both passive and active fire safety means), engineers and architects, and four international experts on building evacuation holding a PhD in the field. The international experts were selected through a post asking for collaboration using LinkedIn, the professional social network, namely at the Pedestrian and Evacuation Dynamics group.

These experts were solicited to rate all the questions in the four sections in the form to be presented to subjects. Then it was made available to all subjects by e-mail. Subjects completed their answers directly into the document and sent the results by e-mail. It is assumed that at least one hour was needed to completely read, think and answer all topics. Some subjects said it took them over 3 hours, not consecutively, including time for reflexion on the scenarios and situations. The process was conducted during four months (from late November 2013 until February 2014). The questionnaires were filled either in the presence of the candidate or using other means such as a combination of e-mail, telephone and Skype.

After the analysis of results, presented later on Section 5.2, the questionnaire was redefined using the inputs and comments from the expert panel and the implementation of the SG begun, as described in next section.

[14] The use of a Likert scale, named after its inventor, the psychologist Rensis Likert, allows participants to state a finite level of difference between the importance of given factors, i.e. a limited variance (Ronchi and Kinsey, 2011) in which respondents specify their level of agreement or disagreement on a symmetric agree-disagree scale

4.6 Serious Game Development

Preliminary experiments were described earlier on Sections 3.6.1 - ModP the pedestrian simulator developed in-house at LIACC); Section 3.6.2 – UWB for tracking pedestrian trajectories using RFID, and Section 3.6.3 – EVA the *"EVAcuation"* fire drill simulator. The former experiment was the test-bed used later for the Conceptualisation of the SPEED methodology.

4.6.1 Modelling the 3D Scenarios

To create a SG with a 3D environment it is necessary to prepare the scenario, either based on a real building or a virtual one (Navarro et al., 2012). This process starts by selecting the model to be used, in 2D or 3D. For existing buildings, such as the Faculty of Engineering of University of Porto (FEUP), architectural blueprints are available in Auto-CAD, but in 2D (see Figure 4.4 image on the left) which needs to be convert to 3D.

Figure 4.4 – FEUP "I" building 1st floor architectural blueprint (2D), 3D model in Blender and 3D rendered view of the building in Unity3D showing LIACC lab I121

A preliminary step to extrude the walls and other vertical elements is needed. This may be achieved by using professional CAD software, such as Revit or AutoCAD, or 3D modelling software, for instance SketchUp or Blender. Then, the scenario needs to be customized by adding furniture, lighting, and other objects such as emergency signs and sound (for instance for the fire alarm).

The methodological approach to create the scenarios is summarized by the following steps, schematically represented in Figure 4.5:

- Use a 3D model of the building (sometimes a 2D -> 3D conversion step is required);
- Import the 3D model into Unity3D;
- Add game features (FPS character controls, sound effects, scenario customization);

- Deployment into executable software version for PC/Laptop or for the web.

FEUP 3D model was developed using Blender by students of the Informatics Engineering department. However, only the external walls were available, so the interior walls, stairs and other vertical elements were missing. After many hours of 3D modelling, the inside of the building was recreated with some degree of reality (Figure 4.4).

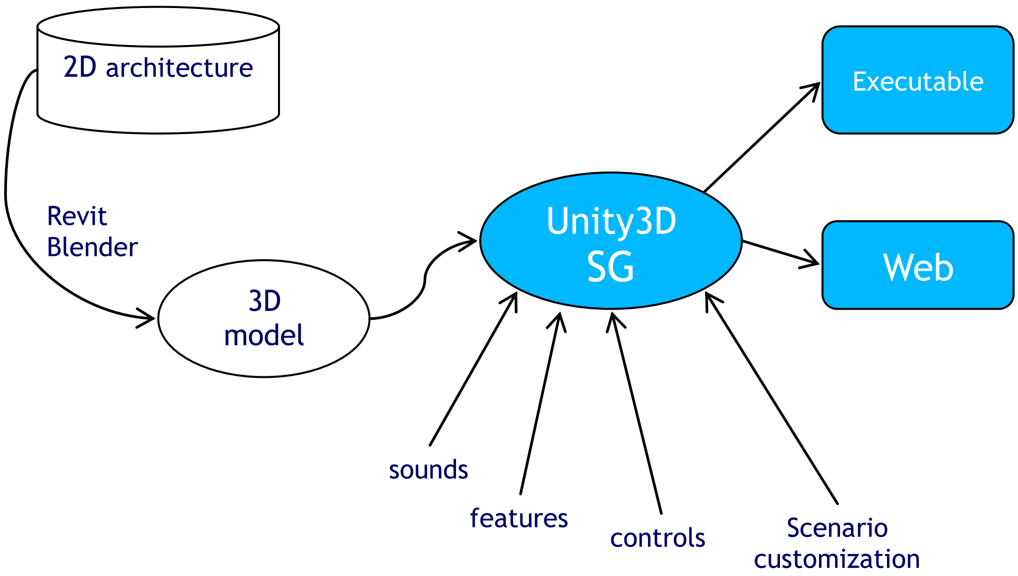


Figure 4.5 – Methodology for the development of the SG test-bed

Another experiment consisted in using a Revit 3D model, customized with 3D elements borrowed from *SketchUp's 3D Warehouse Web Site*[15]. This building 3D model was then converted into a hospital or care centre (Silva, 2013), referred previously in Section3.6.3.

4.6.2 Selecting the Videogame Engine

To select the appropriate game engine, it is necessary to elaborate on the requirements that are needed to support the implementation of the platform suggested in this thesis, using the SG concept. The set of features needed include the following:

- 3D renderer with audio and video playback;

[15] https://3dwarehouse.sketchup.com/ (Copyrighted by Trimble Navigation Limited)

- animation enabling the capability of adding behaviour to objects through transformations, deformations and dynamics;
- physics engine with automatic collision detection;
- a powerful graphical user interface (GUI) that allows visual object placement and property changing during runtime (especially useful to rapidly create new scenarios from existing models and quick tweaking of script variables);
- the ability to develop code in JavaScript, Java, C++ or C#, among common programming languages;
- simple project deployment for multiple platforms without additional configuration, including for the web (which makes it possible to run the game in a web browser and perform massive data collection);
- free and open-source software (FOSS).

Having this list of features, a comparison between the several available game-engines is presented in Table 4.2.

Table 4.2 – Game engines comparison table

Game Engines	**3D video & audio renderer**	**Physics engine & automatic collision detection**	**GUI**	**Programming languages**	**Platforms**	**FOSS**
CryEngine	Yes	Yes	Yes	C++, LUA	Win, Xbox, Playstation	Yes
Java Monkey Engine (JME)	Yes	Yes	Yes	Java	Win, Mac, Linux	Yes
Ogre3D	Yes	Limited	Yes	C++, Java, .Net	Win, Mac, Linux	Yes
Panda3D	Yes	Limited	No	C++, Python	Win, Mac, Linux	Yes
Unreal Development Kit (UDK)	Yes	Yes	Yes	Unreal Script	Win	Yes
Unity3D	Yes	Yes	Yes	C#, Javascript, Boo	Win, Mac, iOS, Android, Wii, PlayStation, Web	Yes

Legend: Win – Microsoft Windows operating system; Xbox – Microsoft videogame console; Mac – operating system developed by Apple for Macintosh computers; Linux – free and open-source software (FOSS) operating system; Android – mobile operating system for smartphones and tablet computers; Wii – videogame console by Nintendo; Playstation – videogame console by Sony; Web – when the game is available for using with a common internet browser such as Chrome or Firefox.

Comparing the features of the game-engines presented in Table 4.2, Unity3D is the one that fulfils all requirements. Although Java Monkey Engine (JME) and Unreal (UDK) have similar features when comparing to Unity3D, this one was favoured because it has the ability of project deployment to the web. Additionally, Unity3D is used by many researchers within the SG community, having a large number of developers, which praises its qualities comparing to the others (J. S. V. Goncalves et al., 2014; Neto and Neto, 2012; Prendinger et al., 2014, 2013; Ronchi et al., 2015; Shoulson et al., 2014; Silva, 2013). Preliminary experiments were made using Panda3D (Ribeiro, 2012), due to its academic background (by Carnegie Mellon University – CMU) and extensive use by Walt Disney Corporation (Crooks et al., 2010; Goslin et al., 2004). However, the physics engine and collision detection methods are not straightforward to use when compared with Unity3D. And this last has a better GUI too. Ogre3D has academic background too, from MIT (Navarro et al., 2012), but has lost preference in past years to Unity3D which has an increasing number of supporters and developers.

After considering all the required features and the arguments put forward it was decided to choose Unity3D for the SG experiments.

4.6.3 Videogame Development Process

The game genre known as First Person Shooter (FPS), widely used in videogames, and particularly in SGs (Bassey et al., 2011; Cowell and Cowell, 2009; Mishima et al., 2013), was chosen for the development of the SGs. FPS games are characterised by placing players in a 3D virtual world which is seen through the eyes of an avatar. This attempts to recreate the experience of the user being physically in the chosen environment and exploring their surroundings. The aim is to give rise to a feeling of immersion in the virtual environment. When playing, the user has the feeling of being actually on the location, moving around, and having the best possible sensation of immersion (see Figure 4.6). FPS games are often related to Role Playing Games (RPG) that engage the player in some sort of virtual adventurous experience (Alexiou, 2012; Magnenat-Thalmann and Kasap, 2009; Prada and Paiva, 2009). RPG games usually introduce some sort of character evolution over time, and the way this evolution happens is part of the game itself, having the player decide how that transformation happens, including character skills and equipment (Ribeiro, 2012). FPS represents a way of virtual reality, commonly used in military games, in which the player is led to explore in a 360º virtual geography, in a war or combat environment (da Silva

Simoes and Ferreira, 2011). When the game context is not military or war combat, FPS games are also called First Person Player (FPP) (Oliveira et al., 2015).

Figure 4.6 – FPS view taken from the “Exit choice” experiment (Oliveira et al., 2015)

The controls for the game follow the common standards for the FPS or FPP genre, using a combination of keyboard and mouse to move the player around the environment. Frequent players will immediately feel comfortable, with no need for warm-up before the game. The complete action mapping is as follows:

- **Mouse movement** - camera control, i.e. where the player is looking at;
- **W** - move forward;
- **S** - move backwards;
- **A** - move to the left;
- **D** - move to the right;
- **F** – open / close doors.

The videogame development process is outlined in Figure 4.5. After having the 3D model, using the Unity3D game framework, the FPP character is created, and the scenario is customized by adding furniture, lighting, and other objects. The game controls are built in the FPP character and intrinsic to Unity3D. The collision avoidance is controlled by Javascript and C# pieces of code (Goldstone, 2009). These are used to control other features as well, such as opening doors or the game sounds (for instance for the fire alarm).

By developing the game under Unity3D, it can be deployed to various platforms, such as Windows, Macintosh and for the web, making it possible to run the game on any computer device, provided that the web browser supports the Unity3D plug-in (Creighton, 2010).

Tracking the character and map where they cross certain limits, in order to trigger an event - for instance, to know when they reached a certain threshold or went through a valid exit (during an evacuation process) - is possible with a technique using invisible colliders (Almeida and Rossetti, 2013).

For the videogame development, there are three key phases: i) game design; ii) integration and iii) multiple scales (Kelly et al., 2007). To address these phases, this section thoroughly details the methodological steps that were undertaken.

The challenge of developing a SG requires ideally the cooperation of a multidisciplinary team composed of game designers, programmers, artists, subject matter experts, instructional designers, among others, to achieve an educational game. However, since the resources to setup such a team are scarce, a pragmatic methodology was put up in order to attain a valid prototype to support the experiments envisaged in the present thesis.

4.7 Summary

The present Chapter encompasses the methodological approach that was devised to elicit human behaviour using serious games coined SPEED. Supported by the literature review presented earlier on Chapters 2 and 3, presenting the background and related works, the way ahead towards SPEED was introduced. Namely, the phases, process flowchart, and sequential tasks were listed and explained. The Conceptualisation of SPEED and the methodological approach, including the experiment design and expert panel validation are introduced as well.

Having envisaged a way to collect data from human behaviour and transform it in usable knowledge for behavioural modelling, a first-class abstraction applied to the behaviour of pedestrians, more specifically, during the process of exiting an unknown building during an emergency situation, was selected as test-bed for SPEED.

The design for validation methodology the questionnaire and experiments, based on the Delphi method and with the help of an international expert panel was presented. Then, the questionnaire structure, sections and questions are put forward, and the evaluation approach unveiled.

This chapter concludes by presenting some considerations on the challenges posed by videogames development and on how to solve the difficulties encountered. In the following chapters the experimental setup is described (chapter 5), and the tests performed and their results are presented (chapter 6).

5. Experimental Setup

5.1 Overview

This chapter describes the experimental setup devised and implemented for human behaviour elicitation using SG in evacuation scenarios. It starts presenting the knowledge elicitation process from the expert panel using the Delphi method, and follows describing the pilot test setup as well as results. It concludes with the description of the final test setup.

5.2 Knowledge Elicitation from the Expert Panel

The elicitation process based on the Delphi method, thoroughly explained earlier on Section 4.5, consist on having the experts answering a set of questions, rating them quantitatively and qualitatively. The sections of the questionnaire as well as the SG scenarios devised were meticulously explained to the experts. Consequently, the questionnaire sent included the preliminary comments made by some of the experts during the invitation and selection of the panel. Therefore, this step has resulted in a document reflecting a good basis for consensus. This methodology had in mind reducing the rounds to reach a consensus to a minimum.

After receiving the questionnaires answered by the experts, the results were analysed using a combination of Microsoft Excel spreadsheet and the Statistical Package for the Social Sciences (SPSS) which consists of predictive analytic tools for multivariate data. The content validity was given by the expert panel with pertinent comments and theoretical information about human behaviour in "fire" scenarios, more specifically during the evacuation process.

5.2.1 Expert Panel Characterization

From the initial set of experts, some failed to answer completely all questions, and consequently were excluded from the final analysis. Therefore, a total of 16 answers were validated.

The majority of the subjects are males (75%) and Fire Safety Engineers (62.5%); of these, 9 (56.25%) hold a Master degree; 25% hold a Ph.D. on fire safety, and more specifically in the area of egress. There are 25% experts related with the fire safety industry and 31.25% that are or were fire-fighters, of which 25% are or were commanders. Table 5.1 shows the main sample group characteristics.

Table 5.1 – Expert panel characteristics

Data	Values
Number of subjects (only valid or complete responses)	16 (100%)
Male subjects	12 (75%)
Female subjects	4 (25%)
Portuguese	13 (81.25%)
Foreigner	3 (18.75%)
PhD in fire safety	4 (25%)
MSc in fire safety	9 (56.25%)
Fire Safety Engineer (with fire safety design experience)	10 (62.50%)
Industry (manufacturers, resellers, engineers)	4 (25%)
Fire-fighters	5 (31.25%)
Fire-fighters commanders	4 (25%)

5.2.2 Result Analysis

The forecast from a Delphi procedure, as stated by (Rowe and Wright, 2001) is taken to be the average of the experts on the final round. Because extreme values can distort means, it is advised to use median that excludes these extreme values. Having selected experts with experience in the domain of application, namely evacuation scenarios, has reduced the occurrence of extreme values.

All questions presented to experts to be evaluated qualitatively use the typical five-level Likert-type scale (1 - Strongly disagree; 2 - Disagree; 3 - Neither agree nor disagree; 4 - Agree; 5 - Strongly agree).

The median of the **first section** of the questionnaire, related to the subject general characterization, presents a high rate of conformity as depicted in Figure 5.1. Median is 5 - Strongly agree (according to the Likert scale) for all features: age (mean=4.94; SD=0.25; max=5; min=4); gender (mean=5; SD=0; max=5; min=5), dominant hand (mean=4.75; SD=0.68; max=5; min=3), education (mean=5; SD=0; max=5; min=5), profession (mean=4.94; SD=0.25; max=5; min=4), computers experience (mean=4.56; SD=0.73; max=5; min=3) and videogames experience (mean=4.56; SD=0.73; max=5; min=3). Aggregate results can be seen in Appendix C.

One expert mentioned that the age could be aggregated for later statistical analysis, but nevertheless agreed with this question. All experts strongly agreed on the gender and education. Regarding the dominant hand, one expert questioned the point to ask this to the subjects; later, when we explained the purpose (to correlate this characteristic with the tendency to turn left or right), the expert expressed some reservations to the validity of that approach. Two experts expressed concerns on asking subjects about their computer and game expertise. However, most experts understood the importance of this information to validate the SG and outwit possible noise in data due to subjects' difficulties on using computer games. One indeed said that computer expertise is arguable, since gaming experience is one of the aspects that should be asked to subjects instead. However it was decided to keep this characteristic since computer expertise is not similar to videogame experience.

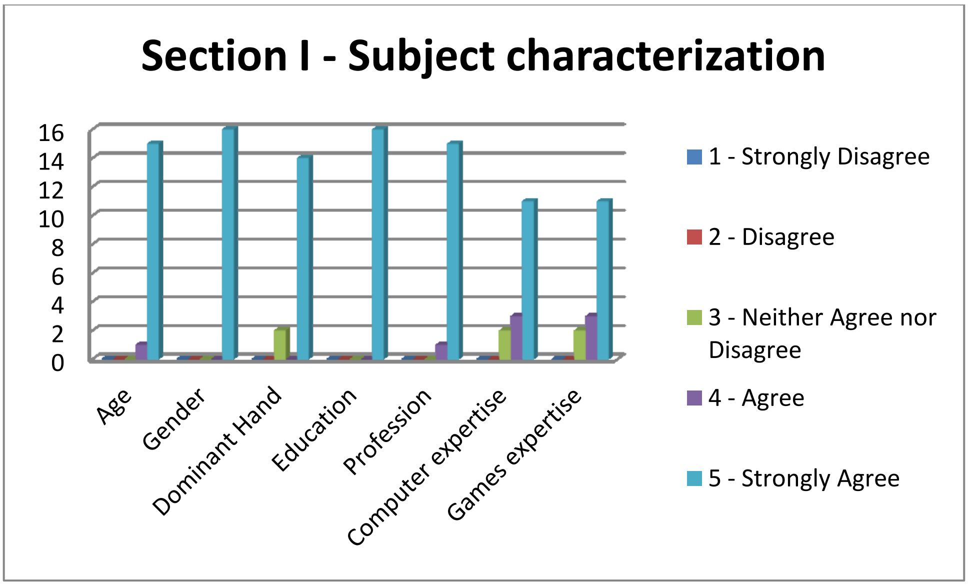


Figure 5.1 - Section I - subject characterization

Section II aim is to characterize the subject regarding his/her fire-safety culture. There are 8 questions on this section: fire training (mean=4.5; SD=1.03; max=5; min=2), fire training areas (mean=4.13; SD=1.31; max=5; min=2), fire training periodicity (mean=4.44; SD=0.89; max=5; min=2), fire-related experience (mean=4.38; SD=0.96; max=5; min=2), where? (mean=4.44; SD=0.89; max=5; min=2), what? (mean=4.38; SD=0.96; max=5; min=2), behaviour (mean=4.44; SD=0.81; max=5; min=2), activity influence (mean=4.25; SD=1.13; max=5; min=2) as depicted in Figure 5.2. Some experts consider that this information is not relevant to characterize the subject and / or to define his/her behaviour. However, the majority of experts understood the scope of these questions and their importance to categorize the subjects. It is expected that this information is somehow correlated with the options and behaviour during evacuations. At least, if such correlation exists, it will emerge from the data collected.

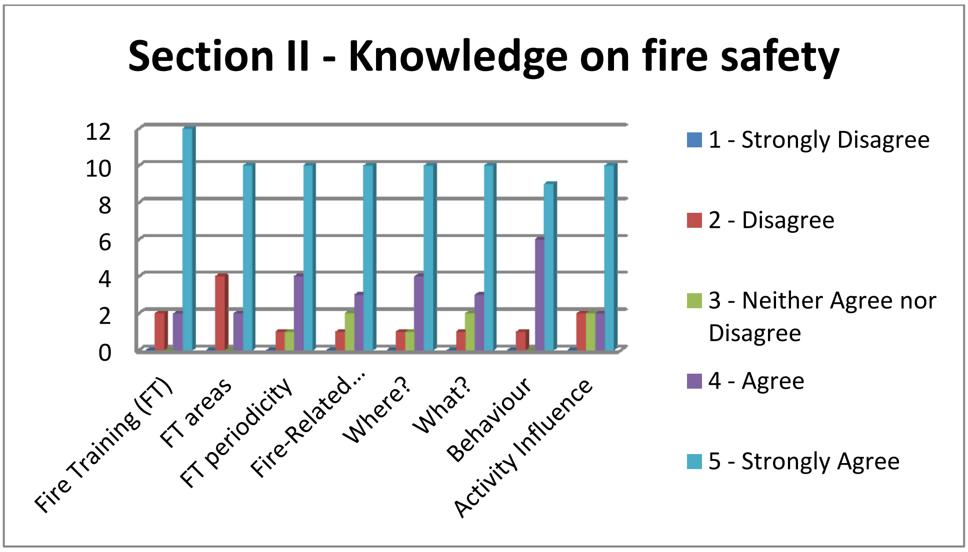


Figure 5.2 - Section II – knowledge on fire safety

5.2.3 Experiments

The first experiment consists in identifying the fire alarm sound (**Fire Alarm Id**). The majority of the experts agreed with this scenario, nevertheless one disagreed and two were neutral (median=5; average=4.34; SD=0.98; max=5; min=1) as depicted in Figure 5.3. After questioning the experts that gave a negative evaluation to this experiment, it was found out that they were not realizing the aim of the experiment. The main purpose is to understand if subjects are aware of sirens and can distinguish among the various possible sounds: fire alarm, theft alarm, emergency vehicle siren, fire truck siren. These four were selected among a possible array of sirens or alarm sounds, because they are the most common ones.

The game description had a preponderance of Agree or Strongly Agree answers (median=5; average=4.5; SD=0.63; max=5; min=3). The questionnaire format, having two possibilities: multiple choice question or free text, divided the experts. However it is clear that more than 60% (10 out of 16) prefers the multiple choice question instead of the free text, to avoid bias and increased difficulty in the result analysis (qualitative versus quantitative analysis).

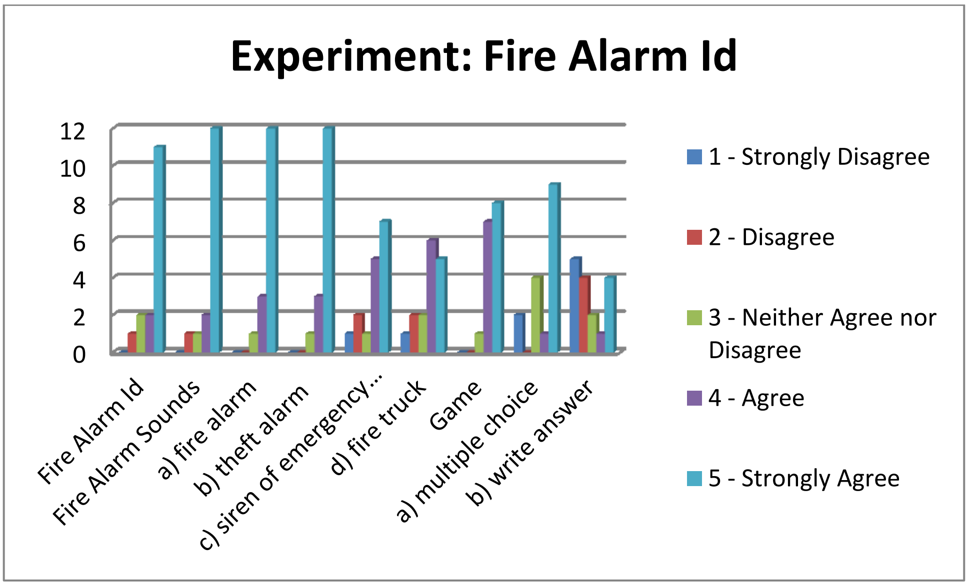


Figure 5.3 – Experiment 1: Fire Alarm Id

The second experiment is related to the reaction of subjects after the siren goes off (**Alarm reaction**). The question is: “*Imagine that you are at home (watching TV or cooking, for instance), in the movies, or at a class and suddenly the fire alarm sounds, what do you do? (select all that apply)*”

And the options are:

- *a) Keep on doing the same activity*
- *b) Call someone (closed family, friends)*
- *c) Try to warn neighbours /other family/colleagues, warning about the fire*
- *d) Call the firemen*
- *e) Call 112/911*
- *f) Search the fire location*
- *g) Try to fight the fire using the portable fire extinguisher*
- *h) Try to fight the fire using fire blanket or a wet cloth*
- *i) Try to fight the fire using water using a bucket*
- *j) Abandon the place immediately without trying to fight the fire*
- *k) Abandon the place only after trying to fight the fire*
- *l) Look for other persons (family / friends)*
- *m) Close the doors behind you when leaving the building*
- *n) Panicked*
- *o) Stay calm*
- *p) Other. Please describe*

Results can be seen in Figure 5.4. The experts gave a high level of agreement to this scenario (median=5; average=4.21; SD=1.11; max=5; min=1), the question presented and to the various possible options a) to p).

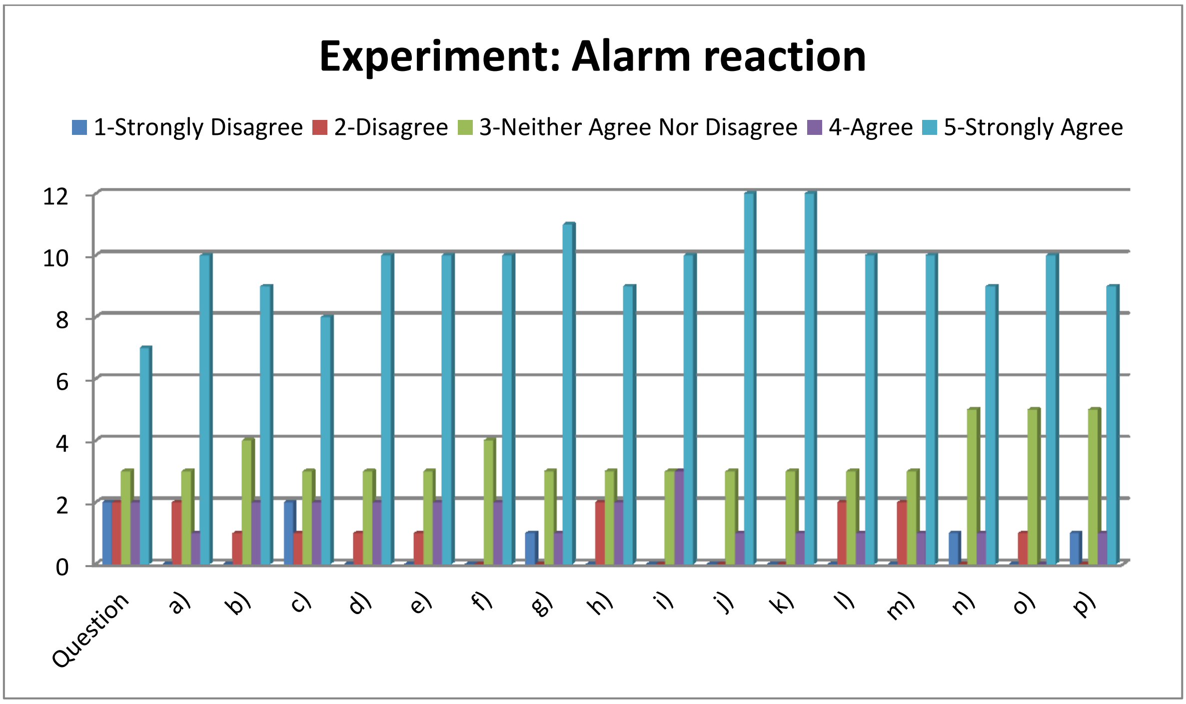


Figure 5.4 - Experiment 2: Alarm reaction

Although the results for each option have a wide acceptance (superior to 60% and sometimes over 75%) it is more important to see the opinions of the experts disagreeing. Some of the experts had rephrasing suggestions to the options. Someone questioned the difference between options b) and c) since they are similar. In fact they need rephrasing, one is related to call (by telephone or mobile) and the other to call by shouting, or searching if they are nearby in the same building. Other experts, namely the non-Portuguese, did not agree with option “n) panicked”; indeed, this aspect, the acknowledgment of panic during evacuation situations, much depends on the definition of “panic” (as discussed in Section 2.4.3) which is not consensual among researchers (Fahy et al., 2012; Marietto et al., 2012; Sime, 1980). One expert strongly disagrees with option p) because says the questionnaire is already too long, and more options are not needed. Two of the experts had strongly disagreed with the question, arguing that the location should be specified, because the reactions, according to them, may vary according to the site. They stated that instead, this question should be repeated for a variety of locations (home, school, work, etc.). However, this would increase the number of possibilities and could lead to “questionnaire fatigue”, a well-known phenomenon that bias results in stated preference surveys (Egleston et al., 2011; Kinsey et al., 2012; Porter and Whitcomb, 2005; Ronchi et al., 2015).

Although this experiment is very interesting, it poses some issues related to the concept, and needs further refinements to reach an agreement among experts. When discussing with the experts more reluctant with this scenario, it became clear that both the questionnaire and the SG are controversial, from evacuation and fire safety point of view. For that reason, and since there are other experiments more consensual, this experiment was not put forward.

The **third experiment (Exit Choice)** goal is to try to establish a behavioural pattern among the subjects who turn to the same side when leaving the room. The question to be presented to the subjects is: "*Imagine you are inside a building in a certain location with two possible exits; suppose that both exits are valid and the distance to the outside is exactly the same; in the condition shown in Fig.1 which exit would you choose, left or right? (see the Figure)*".

This experiment consists in four scenarios, each one with small variations among them. To illustrate the first scenario, two images were designed *Fig1a* and *Fig1b* (as depicted in Figure 5.5) and experts were asked to select the best.

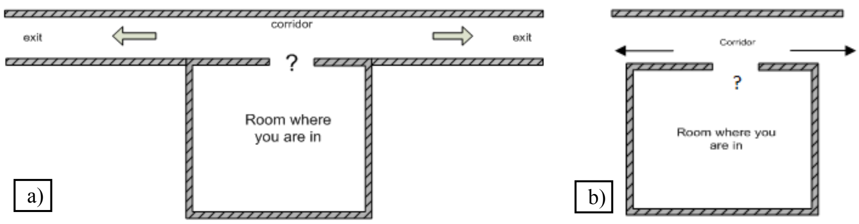


Figure 5.5 – Experiment 3: Room with two possible exits, variant 1 with possible images a) or b)

Experts had no doubt and all (100%) selected *Fig1a* as the best option to illustrate the situation in the questionnaire (see Figure 5.5).

Table 5.2 - Experiment 3 Exit Choice (figure selection)

Experiment 3 Exit Choice	**Fig 1a**	**Fig 1b**
which figure - scene 1	16	0

This first scenario has no sign, so the subject has to decide which exit to use, based on his/her intuition. The goal of the second scenario is to contradict that reaction (turn right) and force subjects to turn left (Figure 5.6a). The purpose of the third scenario is to pose a dilemma to the subject: if the sign is pointing left but the exit is blocked with fire what should they do? Follow the emergency sign and try to pass the fire or go the other way (Figure 5.6b)? The last scenario presents another dilemma: people are running towards the opposite direction pointed by the exit sign; what should one do? Follow the runners or ignore them and go through the left (Figure 5.6c)?

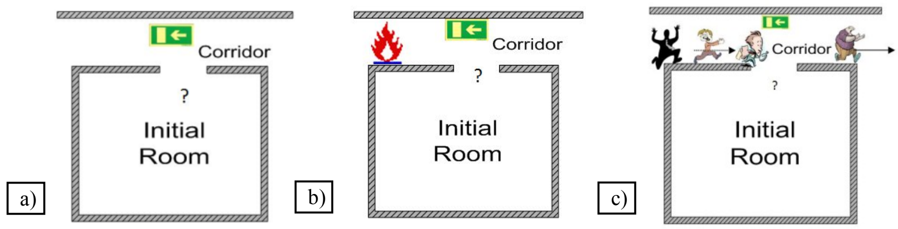


Figure 5.6 – Experiment 3: a) scene 2 with exit sign pointing left; b) scene 3, exit sign pointing left but exit blocked with fire c) scene 4, exit sign pointing left but people running opposite direction of exit sign

The experts' judgment to this experiment was fairly positive (median=5; average=4.33; SD=0.94; max=5; min=2) as depicted in Figure 5.7. There were three experts that missed the point of these questions, especially the first variant in which there is no sign. One argued that this kind of information is not relevant and that the experiments designed will bring no valuable new information. Another said that the scenario should be better contextualized; if subjects have prior knowledge of the building; what path did they took to that room, suggesting that people often use the same way they made to get in. Two further experts said that this kind of experiments has already been address. Indeed, the exit choice experiments were the basis of the Ph.D. thesis by Xie (Xie, 2011) and Nilsson (Nilsson, 2009). However, the experiments proposed in the present work go beyond specific scope of the exit choice problem, since they are part of a wider project, using Serious Games for creating a set of scenarios for behaviour elicitation.

All scenes had a high percentage of positive votes (over 87.5% for agree and strongly agree choices). Scene 1 (median=4; average=4.06; SD=1.06; max=5; min=2), scene2 (median=5; average=4.5; SD=1.03; max=5; min=2); scene3 (median=5; average=4.38; SD=0.89; max=5; min=2); scene 4 (median=5; average=4.38; SD=0.96; max=5; min=2).

Based on the commentaries of four experts, it was suggested that scene 3, where the exit is blocked with fire, to subdivide this scene into two, one with smoke and the other with fire.

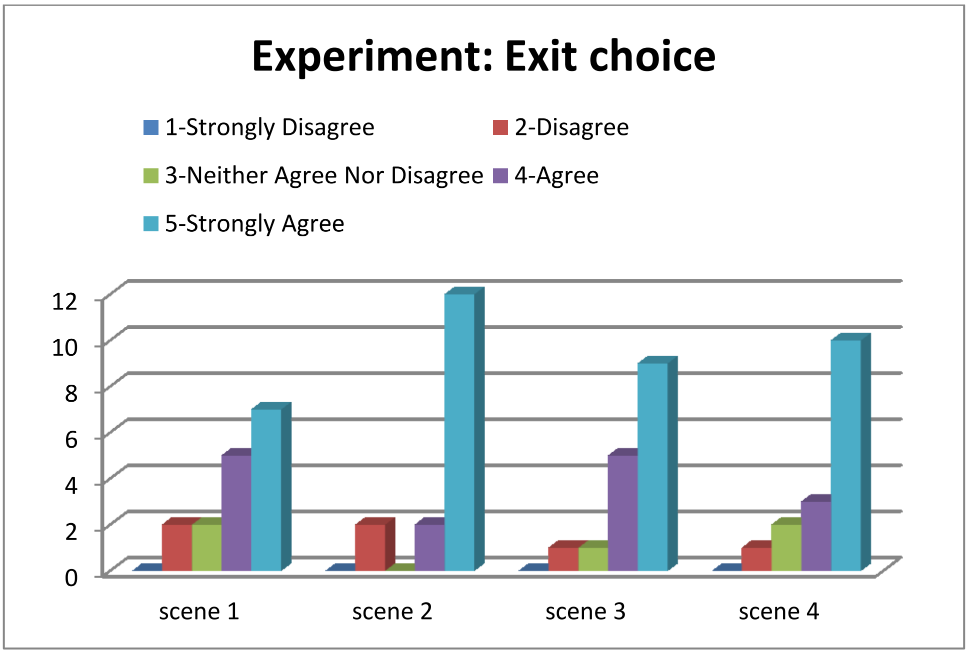


Figure 5.7 – Experiment 3: Exit choice

The **fourth and last experiment (Auditorium)** consists of an auditorium with a certain inclination and entrance on different levels: upper (near the rear of the auditorium) and lower, near the screen or stage.

The inspiration for this test comes from the Portuguese fire codes that establishes that occupants shall egress evenly using both up and down exits when the auditorium has a certain inclination and more than 12 rows[16]. The goal is to assess if the human behaviour is compliant with the assumptions that the legislation uses.

The subject is located in three possible places in the auditorium: up (far from the screen or stage), middle, down (near the screen/stage). The normal entry to the room is either using up or down entries. The experiment goal is to find out which is the exit preference for each of these possibilities.

The questionnaire to be presented is composed of six questions (that can be seen in Appendix A, at the end of Section IV). The graph resulting from the questions presented to the experts (also available in Appendix A and the table with the aggregate results in Appendix C) and their answers can be seen in Figure 5.8.

In addition to the six questions, it was asked to the expert panel if they had agreed with repeating the experiment with three variants:

[16] nr. 3 article 55.º from Portuguese fire code *Portaria* 1532/2008 (Portugal, 2008b)

- Variant 1: the door used to access the auditorium is blocked with fire/smoke;
- Variant 2: the nearest emergency door is blocked with fire/smoke;
- Variant 3: people inside the auditorium are running from the nearest emergency exit, to the opposite direction.

Even though the majority agreed or strongly agreed (87.5%) to the 1st question (median=5; average=4.44; SD=0.89; max=5; min=2) and over 90% to the 2nd (median=5; average=4.61; SD=0.78; max=5; min=2), one expert emphasized on the fact that the number of combinations is very high and this can lead subjects to grow bored and thus bias the results.

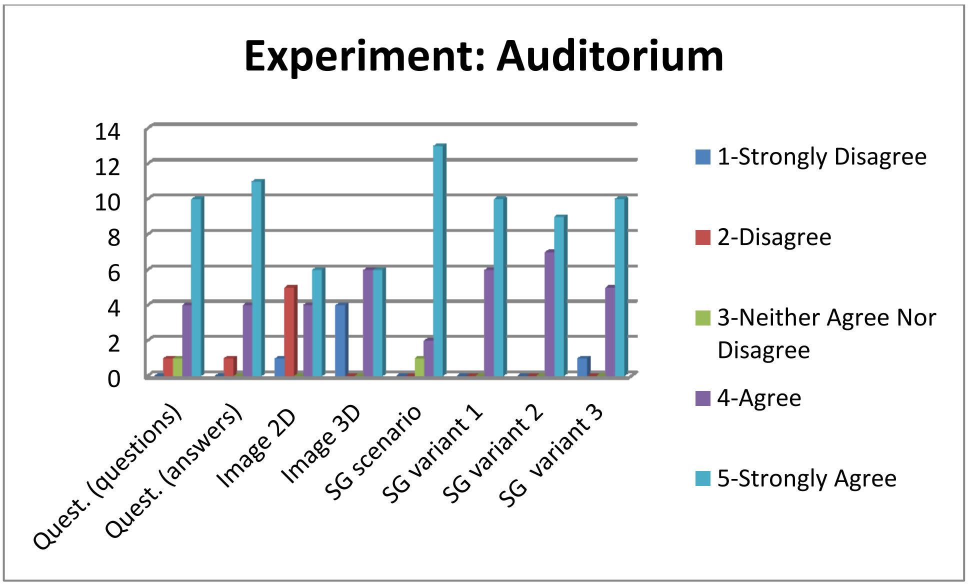


Figure 5.8 – Experiment 4: Auditorium

Two other questions were about the image to be presented to subjects: if its quality is sufficient and clear enough for their perception of the scenario presented (see Figure 5.9) or if more images would be needed. Despite 37.5% disagreed or strongly disagreed, the remaining said that this image is sufficient (median=4; average=3.56; SD=1.46; max=5; min=1). And only 4 experts said that 3D images would help, while the others (75%) considered that this image is clear enough for most people and that more images would make the questionnaire too long (median=4; average=3.63; SD=1.63; max=5; min=1).

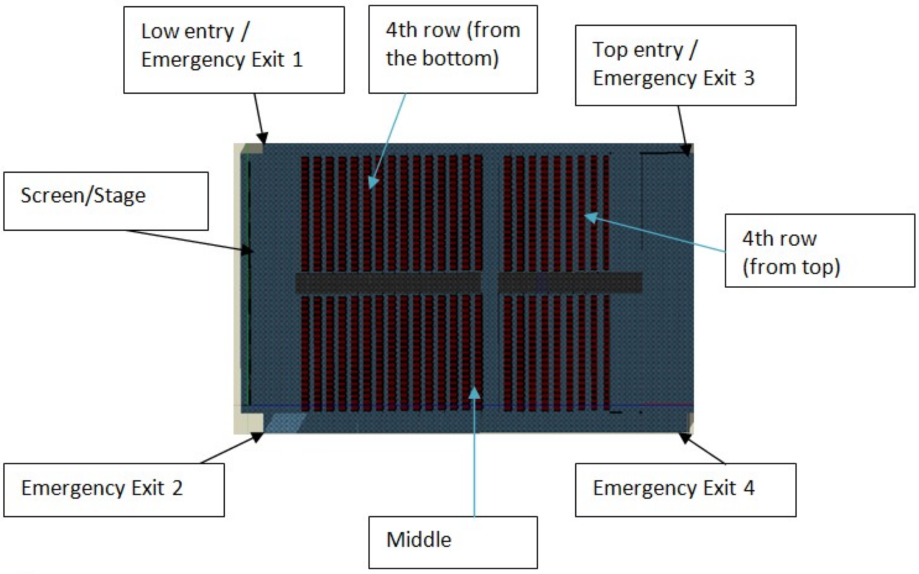


Figure 5.9 – The auditorium scenario showing the entries, exits and the locations where the subject will be seated

The remaining questions presented were related to the videogame implementation (median=5; average=4.75; SD=0.58; max=5; min=3); the three variants were also classified: variant 1 (median=5; average=4.63; SD=0.5; max=5; min=4); variant 2 (median=5; average=4.56; SD=0.51; max=5; min=4) and variant 3 (median=5; average=4.44; SD=1.03; max=5; min=1). Only one expert disagreed strongly on having many scenarios and variants, all the others agreed, having this scenario the highest score among all.

5.2.4 Discussion

The complete Delphi method typically has more than one round. However, as the experts were invited, one by one, for participating in the survey, some technical issues were discussed and the pressing suggestions have been put forward in the questionnaire presented to them, later on. This methodology led to a higher degree of agreement among experts with regarding most of the questionnaire sections and questions. This preliminary round during the put up formation of the expert panel and questionnaire had the outcome of reaching to consensus with only one round.

Nonetheless, the experts issuing critics to specific aspects were interviewed, by e-mail, phone or Skype to explain their opinions and propose alternative solutions.

Sections I and II were unchanged and the same happens with experiment 1 (Alarm Id). The experiment 2 (Alarm reaction) was not put forward, because there is some controversy with phenomena related with pre-evacuation and some concepts, such as the meaning of panic.

Besides, after the first round of the Delphi method, when discussing this issue with some of the experts having concerns about the ways to implement and design this experiment, it became clear that for the behaviour elicitation in the Alarm reaction experiment, additional consensus is needed. Given that the main point of using SG for eliciting behaviour, in what relates to this thesis, is to show the use of the concept, promoting new research directions, but having present that there are limits in time and resources during a PhD research and it is considered that having three different experiments are enough as a proof of concept.

Experiment 3, the exit choice, was selected for the pilot test, because it has four different scenes, the alignment of the questionnaire with the SG was consensual among the experts (opposite to the experiment 2, which was dropped), and provides a good case study and test bed for the SPEED instantiation using SG.

The Auditorium experience was simplified, after the comments of some experts, which recommend to perform the experiment using only two rows (near the top and near the bottom of the room), to reduce the number of combinations and make it easier and less confusing for the players and the subjects answering the questionnaire. The variants were dropped as well. However, this experiment has four iterations, same number of questions. If the three variants were to be implemented this would lead to 16 iterations, turning the game in a fastidious experience.

5.3 Pilot Test

For the Pilot Test phase, described earlier (see Sections 4.4.3 and 5.2.2) it was selected the exit-choice experiment. As explained before, this test consists in trying to study if there is a trend on occupants' behaviour of turning right or left when leaving a room

To compare the SG and questionnaire results, each subject of the selected population had to do both, play the game and complete the questionnaire. This procedure was explained earlier on Section 4.4.5.

5.3.1 The Questionnaire

Whilst the questionnaire was very similar to the one presented to the expert panel for validation (see Section 5.2.3, Figure 5.5 and Figure 5.6), there was an extra question added, so in the end, five questions regarding the same scenario were asked. For the initial question Figure 5.5a was used (see Figure 5.10a). The new question was suggested by some experts, and is related to the corridor blocked with fire (see Figure 5.6b or Figure 5.10d). Some experts suggested said that this question could be divided into two different scenes, one with fire and another just with smoke, to see whether people would try to go forwards and face the smoke (Figure 5.10c).

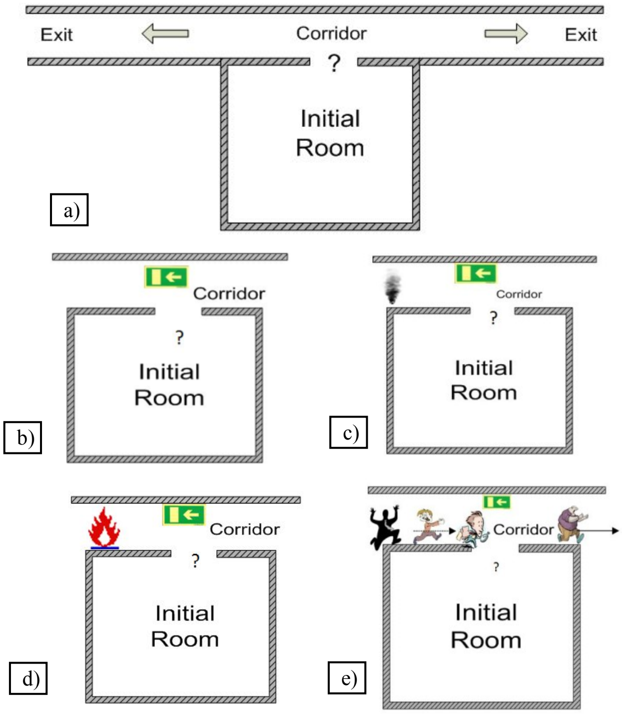


Figure 5.10 - Questionnaire scenarios a) 1: no exit sign; b) 2: exit sign pointing left; c) 3: smoke; d) 4: fire; e) 5: people running opposite direction of exit sign.

5.3.2 The Game Scenario

The game was created in Unity3D based on the comments from the Expert Panel, with five levels, each one corresponding to the five questions of the questionnaire. The first level starts with the player inside the office room. Looking at the image (see Figure 5.11a), the player is initially located at the desk that is positioned on right side, when looking towards the door.

Figure 5.11 - a) Screen view of the initial scenario b) Exit at the end of the corridor.

The experimental scenario consists of an office room leading to a corridor with two possible exits. Both exit options (left or right) have the same length towards an exit door and are completely symmetrical (see Figure 5.12). The player is placed in a hypothetical fire situation, having to evacuate the building as quickly as possible. The choice is to go left or right when leaving the room (see Figure 5.11b). When moving towards the exit, an invisible collider was put in place to end the game level and move forward to next level or return to the main menu. This collider's technique for data collection was thoroughly explained elsewhere (Almeida and Rossetti, 2013).

Figure 5.12– Bird view of building layout with corridors leading to two possible emergency exits.

The first time this scenario is shown, only one exit sign on top of the office entrance is presented (Figure 5.13b). No other cues are given on which direction to take. Player can choose equally to turn left or right. The player is urged to go as quickly as possible to the outside and to find a route to exit the building (Figure 5.11b). This game level will end as soon as the player reaches a valid exit.

The next level starts exactly at the same point, the fire alarm triggers and the player must repeat the process to steering his avatar towards the nearest and safest exit. This time, however, there is an emergency sign pointing to the left (Figure 5.13b). The player is expected to follow the exit sign direction but there is no deterrent if he/she chooses the other way.

The third level starts like the previous one, showing the left turn sign shown in Figure 5.13b and players is expected to follow that direction. However, in this level, there is smoke coming from the end of the corridor (Figure 5.13c). The goal of this scenario is to present the player a dilemma: should she/he go forward despite this obstacle or follow another direction regardless the exit sign points left?

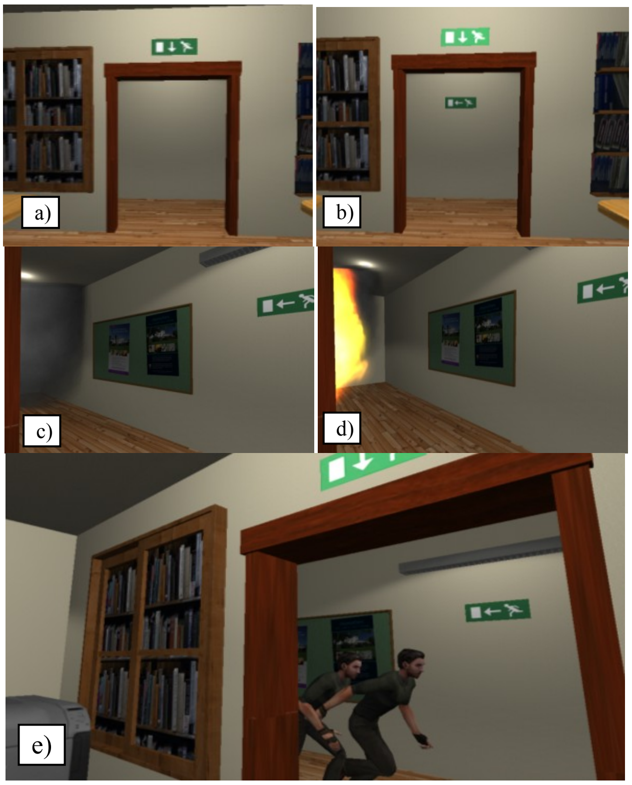


Figure 5.13 - Game levels a) 1: no exit sign; b) 2: exit sign pointing left; c) 3: smoke; d) 4: fire; e) 5: people running opposite direction of exit sign.

The fourth level is again similar to the previous one. The only difference is that besides smoke, there is also fire (Figure 5.13d). To prevent that player tries to pass through the fire this object is set with a collider and is insurmountable. So, all players on this scenario have no other option than escape using the right corridor.

The fifth and last level, presents a different challenge. There is no fire or smoke, but people running from the left towards the right side of the corridor. The goal is to see the reaction of players when having to select between following the exit direction shown in the sign (left) or following crowd moving in the opposite direction (see Figure 5.13e).

All subjects were tutored on the game control usage, keyboard and mouse or joystick, and were given a small time to adapt onto controlling the FPS character and to move around the scenario. The players had no previous knowledge of the scenario and, to allow them all the same chances, each player had only one run, to capture first reactions to the game experience and its controls, to avoid biased data. All subjects played alone and others were kept away to avoid contamination or influence on behaviours. This aspect is an important one to be stressed because it was our expectation to acquire genuine reactions and register genuine choices.

5.3.3 The Population Sample

A total of 22 subjects were selected. The testers can be classified according to the parameters presented in Table 5.3. The data was collected in a questionnaire presented to the subjects at the end of the game.

Table 5.3- Population sample's age and gender

Data	Values
Number of subjects	22 (100%)
Male subjects	13 (59%)
Female subjects	9 (41%)
Minimum age	14
Maximum age	55
Mean age	35
Age SD	14.95
IT experience (as user)	20 Yes / 2 None or little
Videogame expertise	6 Yes / 16 None or little
Fire safety training	5 Yes (23%) / 17 No (77%)

The characteristics of the sample were accessed by statistical measures, such as mean, standard deviation, minimum age and maximum age. The average age of the sample group is 35 years (SD=14.6; min. age = 14; max. age= 55; 13 males; 9 females). The percentage of males is 59% having 41% of females. Almost all subjects have some sort of IT experience with computers; only two subjects admitted almost no knowledge in this area. Six are frequent videogame players whilst the rest have little or none game expertise. Only five said having some sort of fire safety knowledge and training.

5.3.4 Result Analysis

Results of the questionnaire (Q1 to Q5) and the SG (G1 to G5) are presented in Table 5.4 and the percentages in Figure 5.14. It is interesting to note that although the distribution is very similar, there are however some differences that cannot be ignored.

Table 5.4 - Data collected: questionnaire and Serious Game

Questions / game levels	Questionnaire (Q)		Serious Game (G)	
	Left	Right	Left	Right
1) no sign on corridor	6 (27%)	16 (73%)	8 (36%)	14 (64%)
2) sign pointing left	20 (95%)	2 (5%)	21 (95%)	1 (5%)
3) sign pointing left + smoke	4 (18%)	18 (82%)	12 (55%)	10 (45%)
4) sign pointing left + smoke	1 (5%)	21 (95%)	0 (0%)	22 (100%)
5) sign pointing left + people running at the opposite direction	6 (27%)	16 (73%)	6 (27%)	16 (73%)

The goal of the first question (1st level of the game) is to try to establish a pattern of occupants when leaving a room, if there is a trend turning right or left. Beforehand, during the setup of the experiments and the questionnaires, when asking the experts and other people their preference, most subjects (approximately 9 of 10) said they would prefer choose right instead of left. Indeed, over 63% and 73% (respectively in the game and questionnaire) evidenced that hypothesis. Looking closer at the results and having asked some subjects, it is supposed that the initial location has led some players to go forward and left instead of going right. Therefore, further tests are needed to corroborate this hypothesis. Still there are more left turners than initially expected. Behavioural tests will be performed in the future to try and establish a correlation, if any, with psychological dimensions.

The goal of the second question is to counteract that reaction (turn right) and force subjects to turn left. Even with the sign pointing that direction there was one player that missed it and turned right. When answering the questionnaire, two people choose to turn right, regardless the sign, our believe is that they missed the sign and choose the same answer they gave in the first question/scenario.

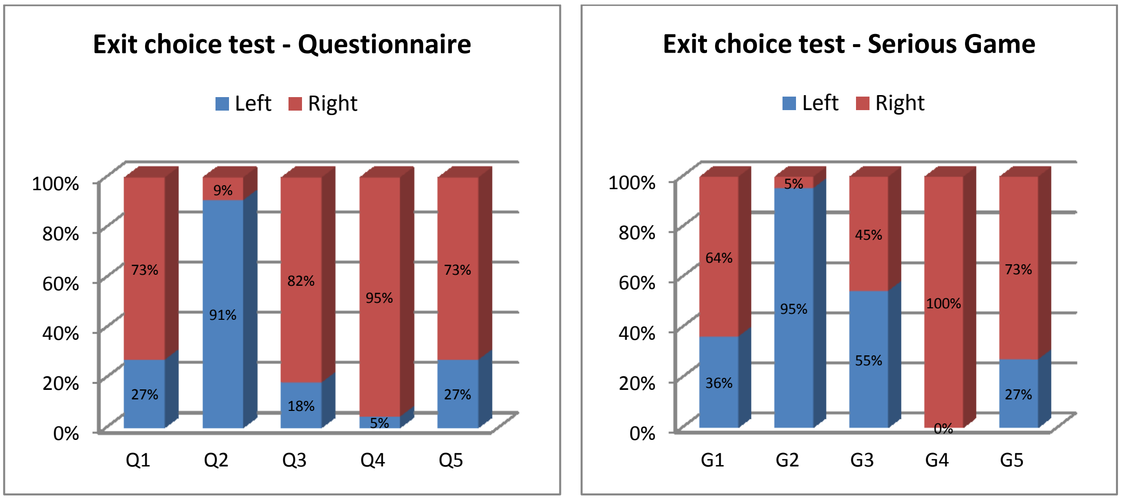


Figure 5.14 – Graphical plot showing the results in percentage for the questionnaire (Qx) and the SG (Gx)

The purpose of the third question is to pose a dilemma to the player: if the sign is pointing left but smoke is coming from that direction what should they do? Follow the emergency sign or avoid the smoke? Some players said that the game should have a command to lower the character and pass right through the smoke. More than half of players decided to face the smoke. This happens due to Unity3D limitations; smoke is dark but gets thinner when approaching thus allowing to be surpassed. When responding the questionnaire, the number of subjects turning right increases a lot compared with the game (18 versus 10, or 81% versus 45%).

Fourth question is similar, but this time fire is strong and all players decided to go back and turn to the right exit using the game (they had no other possibility) but one said would go left facing the fire. We assume that as the previous scenario, that subject either missed the point or decided to challenge giving an unexpected answer.

The last question presents another dilemma: people are running the opposite direction pointed by the exit sign; what should one do? Follow the runners or ignore them and go through the left? Despite a great number of players that choose to follow the people running, more than 63%, some said they prefer to go the opposite direction to avoid crowd and respect the sign. Results to this question were the same at the game and the questionnaire.

A statistical analysis using SPSS was made. Two way frequencies cross tabulation tables, also known as two-way contingency tables for matched pairs, are presented (see Table 5.5). This kind of tables is used when in presence of two samples when each observation in one sample pairs with an observation in the other. Such matched-pairs data commonly occur in studies with repeated measurement of subjects, such as longitudinal studies that that observe subjects over time (Agresti, 2002, chap. 10).

G1 to G5 refer to the SG levels and Q1 to Q5 to the questionnaire questions. Each table corresponds to one question / game level. Columns have the questionnaire (Q1..Q5) and lines the game levels (G1..G5). For each column / row, the frequencies of the choices are presented (right/left). The intersection of columns and rows with different values show the number of subjects that had a similar or different response.

Table 5.5– Two-way frequency cross tabulation tables

Frequency		Q1 – no sign		Total
		Right	Left	
G1 – no sign	Right	14	0	14
	Left	2	6	8
Total		16	6	22

Frequency		Q2 - sign		Total
		Right	Left	
G2 – sign	Right	0	1	1
	Left	2	19	21
Total		2	20	22

Frequency		Q3 – smoke		Total
		Right	Left	
G3 – smoke	Right	10	0	10
	Left	8	4	12
Total		18	4	22

Frequency		Q4 – fire		Total
		Right	Left	
G4 – fire	Right	21	1	22
Total		21	1	22

Frequency		Q5 - people running		Total
		Right	Left	
G5 – people running	Right	13	3	16
	Left	3	3	6
Total		16	6	22

For example, the 1st question (Q1) has 16 subjects turning right; meanwhile the game equivalent level 1 (G1) has 14 subjects turning right and 8 turning left. Analysing the corresponding table, looking at the rows, all 14 subjects choosing right in the game (G1) did the same when answering the questionnaire. But, subjects choosing left, 2 of them had selected right in the questionnaire (Q1). The cell is highlighted. This way it becomes quite clear how many subjects changed their options and in which question/game level.

Looking at the table with the 2nd question / game level, a similar situation occurs: 2 of the 21 subjects that choose left when playing the game (G2) changed of ideas and selected right when answering the questionnaire (Q2). And the one respondent choosing right during the game (G2) selected left at the questionnaire (see highlighted cells). So, although globally only there is only one change when comparing the right/left totals (2 right / 20 left – questionnaire; 1 right / 21 left – game) the truth is that 3 subjects changed their preferences.

The table with the 3rd question / game level show a great number of subjects changing preference; 8 of the 12 subjects that choose left when playing the game (G3) select right when answering the questionnaire (Q3).

Only one subject changed answering left at the questionnaire Q4 having selected right when playing the game (indeed, all subjects went right at this level, when the exit has fire). And on the last level, 3 subjects changed their minds.

Nevertheless, by observing the previous tables it is possible to notice that the majority of the individuals maintain the same decision in the game and in the questionnaire. This is important since the objective is the validation of the questionnaire as a tool to access the behaviour of people in evacuation scenarios.

To verify the statistical test assumptions verification, the Fisher's test was applied in order to show the significance of the association between the results in the questionnaire and the decisions in the serious game by the individuals (see Table 5.6). A significance level of 0.05 was considered for the statistical evidence (see Section 4.4.5).

Table 5.6 – Association between the game and the questionnaire

Association	**Fisher´s test p-value**
G1 versus Q1	<0.001*
G2 versus Q2	1.000
G3 versus Q3	0.96
G4 versus Q4	Not applicable
G5 versus Q5	0.283

In the first case, there are statistical evidences to affirm that G1 and Q1 are associated. In the case (G4 versus Q4) all the participants decided to turn right in the game and only one changed to the left using the questionnaire. For the other cases no statistical evidences of association were found.

5.3.5 Conclusions

The analysis of the data collected at the pilot test gave some preliminary results, important enough to confirm the main goal of the experiment, which consisted on having a preliminary test of the methodological approach for human behaviour elicitation using SGs - in the specific domain of way finding in the evacuation of buildings, comparing the results with stated-preference questionnaires.

After the pilot test, all participants were told to recount their experience and give their contributions on how to improve the game. The use of the joystick was an improvement compared with previous experiments (Ribeiro et al., 2012b; J. F. M. Silva et al., 2013) that some of the participants reported. Subjects that are frequent game players had no problems in controlling the character, using the keyboard plus mouse combination. Three persons had some difficulties to control the character even using the joystick.

From the statistical analysis even though the distribution of answers is similar (Table 5.4), when applying the Fisher's exact test there was only statistical evidence in the first scenario (G1 versus Q1). And G4 versus Q4 (the fire scenario) is the other association due to almost all subject (except one when answering the questionnaire) have chosen the same option. The two-way frequencies cross tabulation tables, or contingency tables for matched pairs (see Table 5.5) show a number of subjects chooses differently when playing the game or answering the questionnaire. Having asked some of the subjects their responses vary. There were subjects that did not recall which option have selected; others said simply they changed their minds. These responses show that subjects may react differently in the same situation, explaining the difficulty to elicit behaviour from the data analysis when detailed. Yet, when looking to the data aggregately some patterns show up and tendencies can be perceived.

Although the population sample of the pilot test is relatively small, the results have fostered the tuning and improvements of the game scenarios. Comments and further analysis of subjects' behaviour were important contributions as well. Furthermore, expanding the experiments to more people and other scenarios, shall lead to more data that can result in knowledge of great importance for researchers of the fire safety field, particularly those studying the egress phenomenon.

5.4 Final Test Setup

After the pilot test, the experiments devised earlier were tuned and improved using the knowledge acquired. Some of the experts were consulted and their valuable opinions were used to get better experimental setups.

Table 5.7 – Summary of experiments

Experiments / scenarios	Design	Expert validation	Pilot test	Final test	Results
1- Alarm ID	√	√	-	√	√
2- Alarm reaction	√	√	-	-	-
3- Exit choice	√	√	√	√	√
4- Auditorium	√	√	-	√	√

Table 5.7 summarizes the experiments devised and the corresponding phases. The exit-choice test was used during all phases. The reason why this happened is because of chronological aspects and implementation issues. The exit-choice scenario was the first to put up and so it was used for the pilot test. As explained earlier in Section 5.2.4, the alarm reaction scenario was not selected to go to the subsequent phases because some experts argued about its design and no consensus was reached. Moreover, this test, according to some of the experts, should be subdivided according the locations (home, school, office, others) combined with a great number of questions, making the experiment too fastidious for subjects. Furthermore, having three different experiments were considered enough, as a proof of concept.

5.4.1 The Alarm ID experiment

The Alarm ID experiment consists on checking if subjects are able to identify and distinguish the fire alarm sound among the various possible sounds: fire alarm, theft alarm, emergency vehicle siren, fire truck siren. These four were selected in the midst of a possible array of sirens or alarm sounds, and validated by the expert panel (see 5.2.3).

The aim of the questionnaire is to assess if subjects consider themselves able to distinguish these sounds. During the game, the siren is heard and the player has to choose one from the four possible alarms/sirens. This experiment was combined with the auditorium scenario, to take advantage of the immersion feeling and have the player focused. As the auditorium scenario is repeated four times, the alarm ID sound is triggered in each run, summing up the four alarms to be identified.

For the questionnaire, the respondents have to say what they think they are able to identify by answering the following questions:

1. Can you recognize the following alarm sounds: fire alarm? (Y/N)
2. Robbery/intrusion alarm? (Y/N)
3. Emergency vehicle? (Y/N)
4. Fire engine truck? (Y/N)

Results from the questionnaire and the game will be compared to see if what people think they know is confirmed when hearing the sounds during the SG. The goal is to assess if the beliefs related with alarm sounds are in line with the subjects' knowledge, and to check out if the level of perceived knowledge with confirmed by the experiment using the SG.

5.4.2 The Exit Choice Experiment

This scenario is basically the same that was used in the pilot test (see Section 5.3). Very few modifications were made, using the comments and suggestions of the players. Basically, the starting point was moved from the right desk to the centre of the room; this is to avoid the tendency of some players to go to the left, influencing their choice. Another improvement consisted on calibrating the mouse (too fast for some players) and adding a joystick to help players less used to digital games, to steering their game character.

The sample group used for the pilot test repeated the final test. This was an important experiment to verify if the options selected during the pilot test were maintained or not. The point here is to establish if people behaviour follows some pattern or is erratic and stochastic

5.4.3 The Auditorium Experiment

The auditorium scenario was briefly explained earlier in Section 5.2.3. The main goal is checking if the human behaviour is consistent with the Portuguese fire codes premises that establishes that occupants shall egress evenly using both up and down exits when the auditorium has a certain inclination and more than 12 rows.

The role play presented to players consists on an auditorium with a certain inclination and entrance at two different levels: upper (near the rear of the auditorium) and lower, near the screen or stage (see Figure 5.15).

Figure 5.15 - Two perspectives of the auditorium.

After analysing the comments of the expert panel it was decided to decrease the number of the initial scenes from six to four. This way it was intended to avoid players fatigue and to reduce the amount of data to analyse, given that the extra two scenes were not that so crucial for the experiment. Another improvement was to combine this scenario with the alarm id scenario (see Section 5.4.1).

The game starts with the avatar entering the auditorium using the top or rear entry and sitting at the top row. Meanwhile a siren alarm sounds and player has to select one of four possibilities: a) fire alarm; b) theft alarm; c) emergency vehicle siren (ambulance); d) fire truck siren. Then, the player is told two select one exit: the top entry which was used to get in or the bottom one. The selected preference is saved and the experiment is repeated for the following combinations: i) using top entry and sitting at top row; ii) using top entry and sitting at bottom row; iii) access through bottom entry and sit at bottom row; iv) enter via same bottom entry and then sitting at top row (see Figure 5.16).

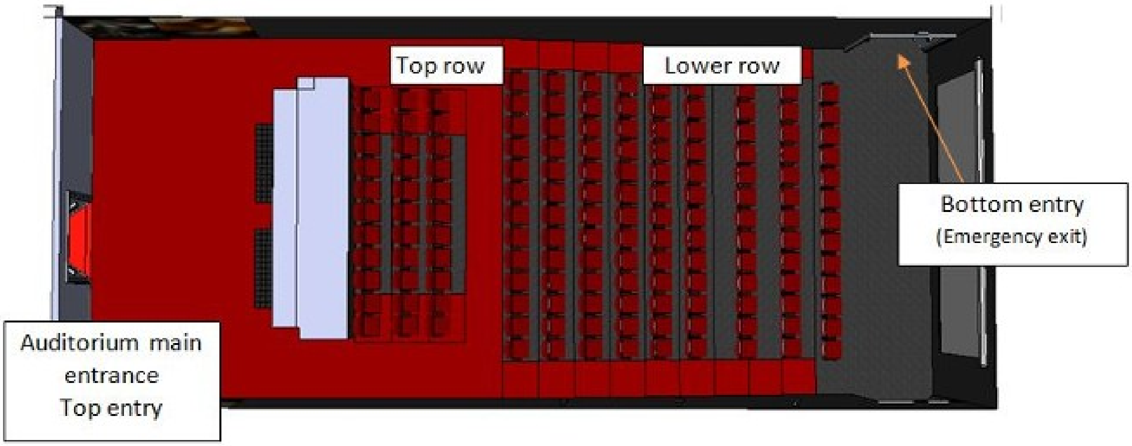


Figure 5.16 – Bird view of the auditorium scenario showing the entries, exits and the locations where the subject will be seated; this was the image presented at the questionnaire

The questionnaire to be presented is composed of six questions (that can be seen in Appendix A, at the end of Section IV).

This experiment goal is to find out which is the exit preference for each of these possibilities: if there is a tendency to exit using the same way in, or using the nearest exit.

5.5 Summary

This chapter presents the steps leading towards the setup of the experiments envisaged and designed for behaviour elicitation using serious games, devised in earlier chapters. The knowledge elicitation phase, conducted with the help of an expert panel using a methodology inspired in the Delphi method, and the results of that process, is thoroughly described. This is followed by a description of the test pilot preparation and setup, another step forward before the final test. The preliminary results show a correlation between the questionnaire and the SG. This promising result, although the population sample is relatively small and some minor adjustments are needed, gave confidence and helped fostering the setup of the subsequent experiments. Players' comments and further analysis of subjects' behaviour were important contributions to improve the game and were used in the preparation of the final test setup.

The following chapter presents the execution of the final experiments and the analysis of results.

6. Experiments and Results

6.1 Overview

This chapter describes the final experiments carried out to collect data of on human behaviour, using questionnaires and serious games for the scenarios devised and presented in the previous chapter. The correspondent results are systematically and statistically analysed. Each section ends with a discussion of the results.

6.2 Final Test Data Collection

For this final test a total of 86 subjects were selected. Similarly to the pilot test, the population sample was divided in two groups with the same purpose. One group filled the questionnaire first and later played the SG; the other group did the same but in reverse order. From these only 62 accomplished to complete both tasks. Each group had precisely 31 subjects.

These testers can be classified according to the parameters presented in Table 6.1.

Table 6.1- Final test population sample's characteristics

Data	Values
Number of subjects	62 (100%)
Male subjects	34 (55%)
Female subjects	28 (45%)
Minimum age	12
Maximum age	76
Mean age	33
Age SD	13.33
IT experience (as user)	59 Yes / 3 None or little
Videogame expertise	29 Yes / 33 None or little
Fire safety training	16 Yes (26%) / 46 No (74%)

This data was collected in a questionnaire presented to the subjects at the end of the experiment. The mean age of the sample group is 33 years (SD 13.33), the youngest being 12 and the oldest 76 years old. The gender distribution is 55% males and 45% females. Almost all subjects have some sort of information technologies (IT) experience with computers; only three admitted having almost no knowledge in this area. Almost half of the subjects, more precisely 29, claimed to be frequent videogame players (47%); 20 subjects admitted having played some videogames but were not frequent players (32%) whilst the remaining 13 had little or no game expertise (21%). Sixteen subjects reported having some sort of fire safety knowledge and training (26%) while the remaining 46 confessed having none or very little fire knowledge or training (74%). To ensure a minimum time distance between playing the game and answering the questionnaire, at least two weeks were required. The date of each activity was recorded, so we could be sure that, except for two subjects that had only 11 and 13 days between tests, this was accomplished. The minimum number of days between each test was 19 days (except the two subjects referred previously) and the maximum 36 days; the average was 27 days and the mode 31 days.

For the statistical analysis the methodology described earlier on Section 4.4.5 is used. In order to test the association between the questionnaire and the serious games in all three experiments, the chi-square test is used. When this test is not conclusive the Fisher's test is used instead. To evaluate the differences between the individuals' options in the game and answers in the questionnaire the McNemar's test on 2x2 tables with pairing is the best suited option (McNemar, 1947). Whenever the p-values are lower than the significant level ($\alpha = 0.05$) this means that there is no statistical evidence of association. A variant test is the binomial sign test giving an exact p-value for the McNemar's test. For a deeper analysis, the two-way frequency cross tabulation tables are used.

The analysis of the results is performed using the Statistical Package for the Social Sciences (SPSS), which consists of predictive analytical tools for multivariate data, will be used in combination with Microsoft Excel spreadsheet.

6.3 The Alarm ID Experiment

6.3.1 Experimental Setup and Sample Characteristics

The description of this scenario was presented earlier on Section 5.4.1. In brief, it consists on checking if subjects are able to identify and distinguish the fire alarm sound among the various possible sounds: fire alarm, theft alarm, emergency vehicle siren, fire truck siren. In the questionnaire the respondents are asked to say if they consider themselves able to distinguish these sounds. When playing the game, one of the sounds is heard and the player has to choose one from the four possible options. The questions in the questionnaire are labelled Q1, Q2, Q3 and Q4, respectively, fire alarm, theft alarm, emergency vehicle siren and fire truck siren. Similarly, in the game, these are labelled G1 to G4.

The sample used for this test comprised 57 subjects from the initial sample of 86 (see details on Table 6.2). Ages range from 13 to 76 (mean=34; median=30; mode=25; SD=14.157).

Table 6.2 – Sample characteristics

Sample characteristics	Mean	Median	Mode	SD	Min	Max
Age	34	30	25	14.16	13	76
Days between SG and questionnaire	41.88	23	17	30.692	10	106
Game Expertise (0=none; 1=some; 2=expert)	1.23	1	2	0.756	0	2

To assure independence of responses, a minimum 10-day separation between answering the questionnaire and the SG was observed. In some cases this separation was higher, reaching 106 days; the mean is 41.88; median=23; mode=17; and SD=30.692. Half of the sample answered first the questionnaire and played the game later; the other half did this on the reverse order, first the game and later the questionnaire. Some of the subjects were asked to fill a personality questionnaire (16PF-5), totalizing 22 subjects in this group.

6.3.2 Results from the Experiment

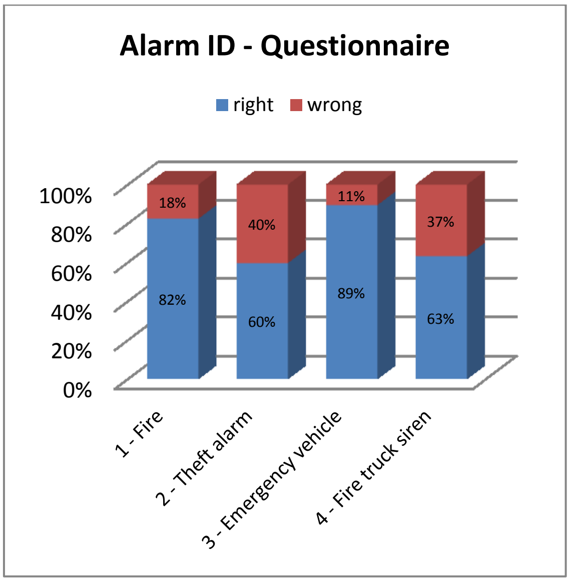
For each alarm sound, subjects had to say their beliefs if they consider themselves able to identify correctly those sounds (a right answer corresponds to 1, a wrong answer to 0) and later, when playing the game, repeat the test but his time listening the sounds. The results are presented in Table 6.3 showing the right and wrong responses.

Table 6.3 – Results from the Alarm Id experiment

Alarm Id	Questionnaire		Serious Game	
	Right answer (1)	Wrong answer (0)	Right answer (1)	Wrong answer (0)
1: fire alarm	47 (83%)	10 (17%)	51 (89%)	6 (11%)
2: theft alarm	34 (60%)	23 (40%)	56 (98%)	1 (2%)
3: emergency vehicle siren	51 (89%)	6 (11%)	51 (89%)	6 (11%)
4: fire truck siren	36 (63%)	21 (37%)	38 (67%)	19 (33%)

Comparing the SG and the questionnaire results, there were a slightly greater number of right answers in the SG than the questionnaire. Particularly in the car theft alarm, that was recognized by almost all subjects (98%). That was due to the SG players actually hearing the alarm or siren sound when answering the questionnaire, and having to guess if they were or consider themselves to be capable of recognizing them. Nevertheless the number of correct answers is greater than 67% (almost more than 90% for alarms 1, 2 and 3)

The sound having a higher rate of right answers is the theft alarm; this is probably because it is very common to hear it in the cities all the time. Fire alarm and emergency vehicle alarm sounds were equally recognized by 89% of subjects. The fire truck siren is less common, and therefore, only 67% of the subjects were able to identify it correctly (see Figure 6.1).



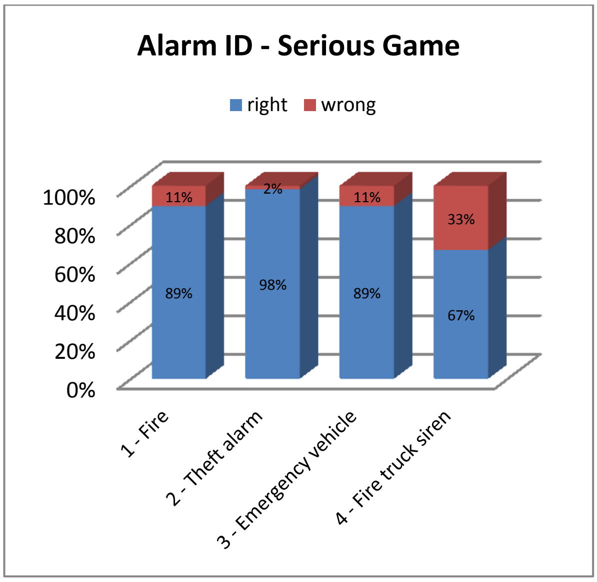


Figure 6.1 – Percentage of right and wrong questions to both the questionnaire and SG

From the analysis of the quantitative data, it is interesting to notice that the perception of the subjects concerning their ability to correctly identify the alarm sounds is quite similar to what they effectively identified when they hear them in the game. However, 40% of the subjects considered they would be unable to identify the sound of the theft alarm, but only 2% actually failed in doing so. Subjects were prudent and conservative, when answering the questionnaire, even though having a higher rate of correct answers when playing the game.

Analysing further the results within the two groups, the one answering the questionnaire first and the game after (Group 1), compared with the participants that played first the game and answered the questionnaire subsequently to (Group 2), it is interesting to notice that subjects from the Group 1 improved the number of right answers from the questionnaire to the game. But the other Group 2 did the opposite; the number of right answers was higher in the game than that in the questionnaire. This may lead to the conclusion that subjects have a better knowledge of alarm sirens than what they think. In the case of subjects playing the game first (Group 2), when answering the questionnaire, some prefer to say they will not recognise the alarm sounds, even if they have correctly identified them in the game. However the differences among the two groups are small as it can be checked by looking at figures in Table 6.4.

Table 6.4 – Results disaggregated with the control group

Alarm Id	Questionnaire first (Group 1)				Serious Game first (Group 2)			
	Questionnaire		Serious Game		Questionnaire		Serious Game	
	Right answer (1)	Wrong answer (0)	Right answer (1)	Wrong answer (0)	Right answer (1)	Wrong answer (0)	Right answer (1)	Wrong answer (0)
1: fire alarm	31 (22%)	4 (3%)	33 (24%)	2 (1%)	16 (18%)	6 (7%)	18 (20%)	4 (5%)
2: theft alarm	25 (18%)	10 (7%)	34 (24%)	1 (1%)	9 (10%)	13 (15%)	22 (25%)	0 (0%)
3: emergency vehicle siren	29 (21%)	6 (4%)	32 (23%)	3 (2%)	22 (25%)	0 (0%)	19 (22%)	3 (3%)
4: fire engine siren	23 (16%)	12 (9%)	25 (18%)	10 (7%)	13 (15%)	9 (10%)	13 (15%)	9 (10%)
Total	108 (77%)	32 (23%)	124 (89%)	16 (11%)	60 (68%)	28 (32%)	72 (82%)	16 (18%)

6.3.3 Association between Serious Games and the Questionnaire

As explained before in Section 4.4.5, the association between the results of the game and of the questionnaire was made using the Chi-Square test; whenever the assumptions were not met, the Fisher's test was the alternative used. To evaluate the differences between the individuals' options in the game and answers in the questionnaire the McNemar's test was used. A significance level of 0.05 was considered for the statistical evidence. SPSS was used to compute the values presented at Table 6.5.

Table 6.5 - Association between the game and the questionnaire

Association between	**p-value (Chi-Square)**	**p-value (McNemar)**
Alarm G1 vs Q1	1 (F)	**0.424**
Alarm G2 vs Q2	0.404 (F)	<0.001
Alarm G3 vs Q3	0.612 (F)	1
Alarm G4 vs Q4	**0.041 (C)**	**0.815**

Legend: (C) Chi-Square for independence test with continuity correction; (F) Fisher test.

Analysing the results shown at Table 6.5, the statistical evidences of the association between the game options and the questionnaire answers are arguable. The Chi-Square test **shows only association in the last alarm sound** (p-value=0.041 < 0.05); however, considering the McNemar test used on pair nominal data, **just the second alarm scenario shows dissociation**. This unexpected outcome was not evident when looking into the results presented in Table 6.3.

Looking deeper into the results, for the two-way frequency cross tabulation tables, considering that "0" means a wrong answer and "1" that the subject hit the answer, it is possible to perceive the subjects that gave different answers, when comparing the questionnaire and the game although globally the SG and questionnaire results are similar (see Table 6.6).

Table 6.6 – Two-way frequency cross tabulation tables

T1_G1 * t1_Q1 Cross tabulation

Count

		T1_Q1		Total
		0	1	
T1_G1	0	1	5	6
	1	9	42	51
Total		10	47	57

T1_G2 * T1_Q2 Cross tabulation

Count

		T1_Q2		Total
		0	1	
T1_G2	0	1	0	1
	1	22	34	56
Total		23	34	57

T1_G3 * T1_Q3 Cross tabulation

Count

		T1_Q3		Total
		0	1	
T1_G3	0	0	6	1
	1	6	45	51
Total		6	51	57

T1_G4 * T1_Q4 Cross tabulation

Count

		T1_Q4		Total
		0	1	
T1_G4	0	11	8	19
	1	10	28	38
Total		21	36	57

Legend: T1_G1 *T1_Q1 – fire alarm (G1 vs Q1); T1_G2 *T1_Q2 – theft alarm (G2 vs Q2); T1_G3 *T1_Q3 – emergency vehicle siren (G3 vs Q3); T1_G4 *T1_Q4 – fire engine siren (G4 vs Q4).

The fire alarm was recognized correctly by 9 subjects that said in the questionnaire they would fail (T1_G1 vs T1_Q1). The opposite was the case for 5 subjects, which failed in the game although having said in the questionnaire they would recognize the fire alarm. A total of 42 subjects expecting to identify correctly the fire alarm siren did it in the game. There was only one subject saying that he would not recognize the sound, and indeed failed the game test. The number of subjects that changed their response was 14 (24.5%).

For the second test (T1_G2 vs T1_Q2), the theft alarm sound was recognized by all the 34 respondents that said to do so in the questionnaire; however 22 subjects expecting to fail that identification did it correctly during the game. One subject failed both the game and the questionnaire. The number of subjects that changed their response was 22 (38.5%).

All the 6 subjects expecting to fail the emergency vehicle siren test (T1_G3 vs T1_Q3) in the questionnaire identified it correctly during the game; on the other hand other 6 subjects failed to do so having said the contrary in the questionnaire. Nevertheless 45 subjects expecting to identify correctly this sound actually did so in the game. The number of subjects that changed their response was 12 (21%).

The fire engine siren is the test having more discrepancies between the game and the questionnaire (T1_G4 vs T1_Q4). From the 21 subjects expecting to fail only 11 did so in the game. Meanwhile 8 respondents saying that they would recognize this sound in the questionnaire failed to do so at the game, even though 28 confirmed their expectations correctly. The number of subjects that changed their response was 18 (31.5%).

Table 6.7 – Association between the scenes and gender

	p-value (chi-square)		p-value (McNemar)	
Association between	**Male**	**Female**	**Male**	**Female**
Alarm G1 vs Q1	*0.301 (F)*	*0.555 (F)*	*0.375*	*1*
Alarm G2 vs Q2	*0.355 (F)*	*NA*	*0.002*	*NA*
Alarm G3 vs Q3	*1 (F)*	*1 (F)*	*0.727*	*0.625*
Alarm G4 vs Q4	*0.097 (F)*	*0.095 (F)*	*0.109*	*0.289*

Legend: (C) Chi-Square for independence test with continuity correction; (F) Fisher test; NA - not applicable.

Looking at Table 6.7, and using the chi-square test, there is no statistic analysis evidences to support that the gender has impact on the results, because all p-values are greater than 0.05 (there is no data for females - test G2 vs Q2). The McNemar's evidencies dissociation on the theft alarm sound (p-value < 0.05), confirming that there is no association for males on this test.

Table 6.8 – Association between fire-training experience and the results

	p-value (chi-square)		p-value (McNemar)	
Association between	**Yes**	**No**	**Yes**	**No**
Alarm G1 vs Q1	*NA*	*1*	*NA*	*0.774*
Alarm G2 vs Q2	*NA*	*0.457*	*NA*	*<0.001*
Alarm G3 vs Q3	*NA*	*1*	*NA*	*0.075*
Alarm G4 vs Q4	*0.364*	*0.075*	*0.250*	*1*

Legend: (C) Chi-Square for independence test with continuity correction; (F) Fisher test; NA - not applicable.

Considering the fire training experience, the statistical analysis shows no association between this aspect and the results (see Table 6.8). Again, the McNemar test is not conclusive, except for theft alarm (G2 vs Q2) having p-value < 0.05 and vehicle siren test (G3 vs Q3) for which the p-value is slightly greater than 0.05.

6.3.4 Qualitative Analysis

In order to better understand the results obtained quantitatively, some of the subjects with different answers in the questionnaire and the game were interviewed. The ones that failed the questionnaire but answered correctly in the game said that before hearing the alarm sounds, they were unsure if they would recognize them, and therefore, stated that would probably fail. But once they heard the alarms when playing the game, they recognize them immediately. This explanation is observable for the subjects that in Group 1.

Yet, some participants from Group 2, who played the game first, although correctly identifying the alarm sounds, said in the questionnaire they would not be able to so. This may lead to the conclusion that the correct answer was a matter of chance rather than a conscientious guess based on knowing and correctly identifying the sound.

Having asked a few subjects about this issue, they said that there is a wide variety of alarm sounds, including intruder and access control, fire, gas leak, burglar, without a standardised frequency or sound, making them immediately recognizable and identified. At least three participants suggested that the industry, governments or some regulatory association should define a standard to be used by all vendors, ending the present quantity of different alarms.

6.3.5 Conclusions from the Alarm Id Experiment

The noise pollution in modern cities can make it difficult to distinguish among the various sirens and alarms in case of a fire. This has led to this test with the main goal of trying to realize if people can recognize among various alarm sounds the one corresponding to the fire alarm.

Sirens and alarms have different meanings: besides fire, there are alarms from anti-theft devices, emergency vehicles or the fire engine trucks. Comparing the answers of a questionnaire asking the participants if they consider themselves able to distinguish these sounds with the results of the same subjects having to identify those alarms while playing a videogame, provides some insights into the knowledge level people have regarding this matter.

Having in mind that the sample has some limitations, there are some interesting conclusions that might be used by fire experts, safety and security devices manufacturers and authorities related to these aspects.

A high number of participants, more precisely 74%, expected to identify correctly the alarm sounds, and indeed 86% did it. The expectations were exceeded. The fire engine truck had the lowest values, having 67% of participants correctly identifying it, which is still a good number. Regarding the fire alarm, the percentage of correct answers is higher; almost 90% identified it accurately.

However, the statistical tests did not reveal a clear association between the questionnaire and the SG. This is because many subjects (more precisely 14 on the first test, 22 on the second, 12 on the third and 18 on the fourth) performed differently in both situations. However, when looking globally, the values are quite similar. This experiment has shown that the ability to correctly identify the sounds presented (in the game) is higher than their perception (answers to the questionnaire), and this is an interesting outcome. To improve the quality and quantity of the elicited knowledge, more experiments and with more sounds are needed.

Correctly identifying the alarm sounds and perceiving their meaning is of major importance, since time is a crucial aspect in case of a fire, and people must react accordingly taking the necessary actions as soon as possible, after hearing a fire alarm. The sooner the people identify it properly and associate the fire alarm to an emergency event, the faster they will react increasing the probability of surviving and diminishing the number of casualties. Ultimately, in such emergency situations, when every second counts, this recognition might save lives. Therefore, knowing people's reaction and ability of identifying correctly the meaning of alarm sounds is of crucial importance for safety.

6.4 The Exit choice Experiment

6.4.1 Experimental Setup and Sample Characteristics

The exit choice scenario was used for the pilot test and was presented earlier on Section 5.3. Similarly to the naming convention used before, the questions answered by filling a questionnaire are labelled Q1 to Q5; similarly, the game levels (scenes) are labelled G1 to G5.

The sample used for this test comprised 62 subjects from the initial sample of 86 (see details on Table 6.2).

6.4.2 Results from the Experiment

Results of the questionnaire and the SG are presented in Table 6.9. Although the distribution is similar, there are some differences that cannot be ignored. For this test, a higher number of valid responses were validated, totalising 62.

The goal of the first question, Q1, (1st level in the SG, G1) is to try to establish a pattern of occupants when leaving a room, if there is a trend turning right or left. As noted above in Section 5.3.4, when analysing the pilot test results, it was expected that a great percentage of people would prefer choose right instead of left. Indeed, the percentage in the pilot test of right turners was 63% and 73% (respectively in the game and questionnaire). However, in this final test, there are more left turners than initially expected (34% and 42% respectively in the questionnaire and the game). Behavioural tests will be performed to try to establish a correlation, if any, with character aspects. It is expected to find a psychological dimension to be related with this option.

Table 6.9 – Data collected for the exit choice scenario

Questions / game levels	**Questionnaire**		**Serious Game**	
	Left	**Right**	**Left**	**Right**
1) no sign on corridor (Q1/G1)	21 (34%)	41 (66%)	26 (42%)	36 (58%)
2) sign pointing left (Q2/G2)	62 (100%)	0 (0%)	62 (100%)	0 (0%)
3) sign pointing left + smoke (Q3/G3)	18 (29%)	44 (71%)	30 (48%)	32 (52%)
4) sign pointing left + fire (Q4/G4)	0 (0%)	62 (100%)	0 (0%)	62 (100%)
5) sign pointing left + people running at the opposite direction (Q5/G5)	16 (26%)	46 (74%)	22 (35%)	40 (65%)

The goal of the second question is to counteract that reaction and force subjects to turn left. Whilst in the pilot study there was one player that missed it and turned right, in this final test all subjects followed the sign both in the questionnaire and in the SG.

The purpose of the third question is to pose a dilemma to the player: if the sign is pointing left but smoke is coming from that direction what should they do? Should they follow the emergency sign or avoid the smoke? In this scene there is some discrepancy when comparing the questionnaire answers to the SG selections. Almost 50% of the SG players turned left, going through the smoke whilst only 29% choose that option when answering the questionnaire. Some players said that the game should have a command to lower the character and pass right through the smoke. A possible explanation is smoke is not thick enough when player move into it. The immersion process fails by lacking the smell of the smoke and the higher air temperature.

The fourth question is similar, but this time fire appeared more intimidating and all players decided to go back and follow to the right exit. In this scene there are no discrepancies between the questionnaire and the SG. The association between them is absolute.

The last question presents another dilemma: people are running to the opposite direction as pointed by the exit sign; what should the player do? Follow the runners or ignore them and go on through the left? Despite a great number of players that chose to follow the people running, more than 63%, some said they would prefer to go the opposite direction to avoid the crowd and follow the sign.

6.4.3 Association between Serious Games and the Questionnaire

In order to observe the association between the results of the game and of the questionnaire, the Chi-Square test was applied and when the assumptions were not fulfilled the Fisher's test was the alternative used. A significance level of 0.05 was used for the statistical evidence. To evaluate the differences between the individuals' options in the game and answers in the questionnaire the McNemar's test was used (see broader explanation in Section 4.4.5).

Table 6.10 shows the p-values for both the chi-square and McNemar's tests. In order to observe if there is association between the game options and the questionnaire the chi-square test is used. For scenes 2 and 4, as the responses are identical in both the SG and questionnaire the association tests are not applicable, since the association is complete. And for scenes 3 and 5 the p-values $< \alpha$ ($\alpha = 0.05$) showing that there is a statistical evidence of association. The only scene with no statistical evidence of association is the first one.

Table 6.10 - Association between the game and the questionnaire

Association between	p-value (Chi-Square)	p-value (McNemar)
G1 vs Q1	0.143	0.405 (C)
G2 vs Q2	Not applicable	Not applicable
G3 vs Q3	**0.007 (C)**	**0.012**
G4 vs Q4	Not applicable	Not applicable
G5 vs Q5	**<0.001 (C)**	0.109

Legend: (C) Chi-Square for independence test with continuity correction.

In terms of differences between the individuals' options in the game and answers in the questionnaire, only the third question has significant differences. The McNemar's test is used for paired samples to evaluate the answers from the same subject to questionnaire and SG (see 3rd column of Table 6.10). This shows enough evidence to say that only in scene 3 there is a significant difference between the questionnaire and the SG (p-value=0.012 < 0.05).

Dividing the sample according to the gender (see Table 6.11) question 3 shows no association for males (chi-square p-value=0.463) but has association for females (p-value for Fisher's test=0.001 < 0.05). However the McNemar's test shows statistical evidence of dissociation for females (p-value=0.031 < 0.05) when considering their individual preferences.

Table 6.11 – Association between the scenes and gender

Association between	p-value (Chi-Square)		p-value (McNemar)	
	Male	Female	Male	Female
G1 vs Q1	0.587 (C)	0.2 (F)	0.791	0.508
G2 vs Q2	Not applicable	Not applicable	Not applicable	Not applicable
G3 vs Q3	0.463 (C)	**0.001 (F)**	0.180	**0.031**
G4 vs Q4	Not applicable	Not applicable	Not applicable	Not applicable
G5 vs Q5	**0.001 (F)**	**0.001 (C)**	0.125	1

Legend: (C) Chi-Square for independence test with continuity correction; (F) Fisher test.

Table 6.12 shows the association between the scenes (both SG and questionnaire) and with fire training. Behaviour is consistent in the 3rd question: here we can verify that subjects with fire training experience have the same response in both the SG and questionnaire whilst the others do not have the same uniformity. This is a possible explanation for the differences noted: **subjects without fire training have an erratic behaviour while others will take the same actions in a more consistent way**. It is also interesting to note that out of 16 subjects with fire training only 5 are female (approximately 1/3 of the subjects).

Table 6.12 – Association between the scenes and fire training experience

Association between	p-value (Chi-Square)		p-value (McNemar)	
	Yes	No	Yes	No
G1 vs Q1	1 (F)	0.176 (F)	0.219	1
G2 vs Q2	Not applicable	Not applicable	Not applicable	Not applicable
G3 vs Q3	0.315 (F)	**0.025 (F)**	1	**0.007**
G4 vs Q4	Not applicable	Not applicable	Not applicable	Not applicable
G5 vs Q5	**0.035 (F)**	**0.001 (F)**	1	0.125

Legend: (C) Chi-Square for independence test with continuity correction; (F) Fisher test.

6.4.4 Pilot Test versus Final Test

Eighteen of the pilot test subjects also took part in the final test. Comparing their responses to the pilot test and final test, it was found that half of them changed at least one or more answers. Looking to the statistical analysis results presented in Table 6.13 the differences between the answers to the pilot test and to final test is statistically significant. Scenes 2 and 4 have similar responses and the test is not applicable (since all or almost all subjects selected the same exit way). It is interesting to notice though that the only scene with association is the first scene in the questionnaire (p-value=0.008); for the SG at the same scene there is no association (p-value=0.533 >> 0.05), meaning that the responses in the questionnaire show a strong statistical evidence of association, although this is not the case in the game. The McNemar's test, when applicable, shows no dissociation.

It can be argued that the changes made in the initial location of the subject, from the pilot test to the final test, had an impact on players' decision to prefer left. Another possible explanation is that the subjects changing their minds were eager to explore the left corridor. The latter hypothesis was indeed verified when asking two subjects that changed their options from the pilot test to this final one. They said precisely that were curious to try the other way out. **This is evidence that some people change their minds and give different answers to the same questions at different times.**

Table 6.13 - Comparing the results between the pilot test and the final test

Association between	p-value (Fisher)	p-value (McNemar)
G1 pilot test vs G1 final test	0.533	1
G2 pilot test vs G2 final test	Not applicable	Not applicable
G3 pilot test vs G3 final test	0.576	0.227
G4 pilot test vs G4 final test	Not applicable	Not applicable
G5 pilot test vs G5 final test	0.107	1
Q1 pilot test vs Q1 final test	**0.008**	1
Q2 pilot test vs Q2 final test	Not applicable	Not applicable
Q3 pilot test vs Q3 final test	1	1
Q4 pilot test vs Q4 final test	Not applicable	Not applicable
Q5 pilot test vs Q5 final test	0.553	1

Legend: (C) Chi-Square for independence test with continuity correction.

6.4.5 Association between Tests and Psychological Dimensions

To better understand the reasoning process in decision-making and to test if there is any association between the responses and psychological factors, some of the volunteers were asked to do a 16 PF-5 test.

This test consists in profiling some of the personality characteristics, by means of a questionnaire. As a result of years of factor-analytic research, sixteen personality factors were identified (16 PF), as described earlier on Section 4.4.2. The test is composed of 185 questions and it lasts almost one hour to complete. The results were obtained using the CEGOC on-line platform[17].

Table 6.14 - Relation between the questionnaire results and psychological dimensions

Association between	Ext	Ans	Tou	Ind	Sel
G1	1	0588	0.188	1	0.637
G2	NA	NA	NA	NA	NA
G3	0.066	0.588	0.664	1	0.153
G4	NA	NA	NA	NA	NA
G5	**0.038**	1	1	0.620	1
Q1	0.316	0.245	0.638	0.620	0.6120
Q2	1	1	0.444	1	1
Q3	1	1	0.152	0.131	0.620
Q4	1	1	0.444	1	1
Q5	0.596	1	1	0.294	0.294

Legend: Ext - Extraversion; Ans - Anxiety; Tou - Toughness;Ind - Independence; Sel - Self-confidence; NA - Not applicable.

Based on this normal-range personality traits for which the instrument is named, there are five broad dimensions – also known as the "Big 5" factors: i) Extraversion; ii) Anxiety / Neuroticism; iii) Tough-Mindedness; iv) Independence; v) Self-Control (Costa and McCrae, 1992).

Table 6.14 shows p-values resulting from the application of the Fisher's test, to the association between the scenes (both SG and questionnaire) and the five personality dimensions for the eighteen volunteers (of the initial 62 sample) that performed the 16 PF-5 test.

The only statistical evidence of association is in scene 5 (but only for the SG) and the extraversion personality dimension. Perhaps the sample is too small or effectively there is no association between the personality factors and the scenes presented to the subjects at this test. Further studies on this subject are necessary. Some researchers have pursued this path but for creating agents not for the behaviour elicitation (Durupınar et al., 2011; Larios, 2012; Zoumpoulaki et al., 2010).

6.4.6 Conclusions from the Exit Choice Experiment

The exit choice test main goal is to find out if there is a trend of subjects to turn right or left when exiting from an unknown location, and their reaction to different situations, such as lack of

[17] http://www.cegoc.pt/ (using access code provided by the Psychologist Liliana Mendes)

indication, signalling pointing a specific direction, having the exit blocked with smoke or fire, and watching people running from the suggested escape direction.

The **statistical analysis shows that there is a strong association between the questionnaire and SG** except for the first scene for which there is not such evidence. The **gender and fire training only revealed some association for the 3rd scene (when there is smoke)**, for which people with fire training show a consistent behaviour, between the questionnaire and the SG. **Regarding the psychological dimensions, no relevant association was found**, except in one case, for extraversion in the 5th scene (people running in opposite direction of sign).

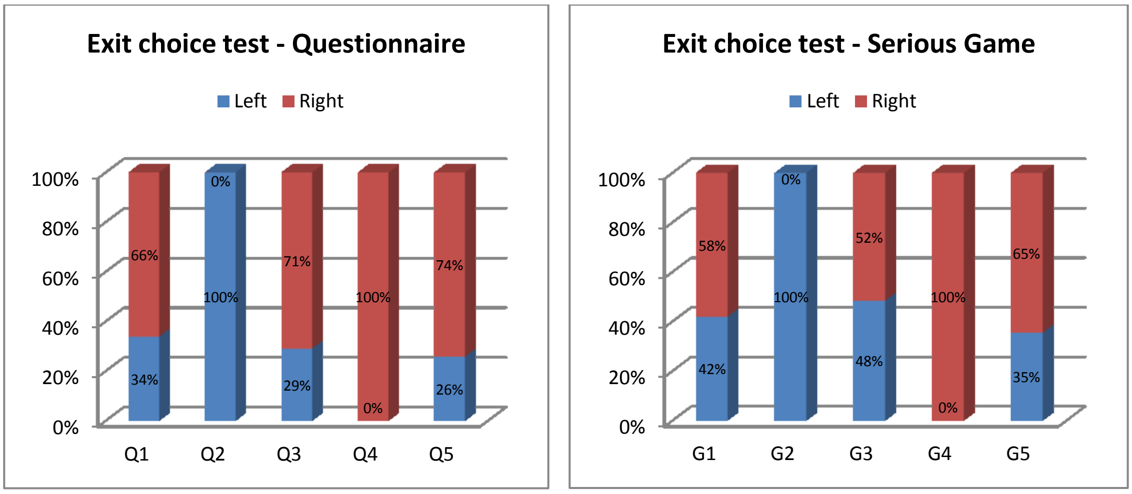


Figure 6.2 - Graphical plot of the results for the Exit choice test for the questionnaire and SG

Looking at Figure 6.2 it is observable that the results from both the questionnaire and the SG are quite similar. When no indication on which side to choose, there is a clear preference for turning right. This might be because our traffic rules point on that direction. It would be interesting to perform this test with a population sample from a country where they perform differently (such as the UK) to see if the results would be the reverse. The results of the 2nd scene, in which the emergency sign is pointing towards the left direction, present no surprise; all subjects respected the indication, both in the questionnaire and the SG. A similar situation happens in scene 4, when subjects face the exit blocked by fire, they all turn back and go on the opposite direction. **The smoke scene has a biased result: almost 50% of the subjects when playing the game follow the direction filled with smoke, whilst only 29% of which dare to do so, when answering the questionnaire. This particular scene evidences the differences between answering to a hypothetic question in a paper survey and having to deal with the situation in a virtual environment, since in the game the smoke presents no danger to the player, because it has no smell and no temperature**. The last scene has some small differences between the questionnaire and the game, but the trend is clearly towards right, meaning, most **subjects prefer to follow others** (74% on the questionnaire and 65% on the SG).

This test reveals some tendencies of subjects when having to exit a space with a binary decision to take: turn right or left. The results elicited in the various possible situations presented before, show that subjects indeed choose accordingly. Instead of using a 50% probability, other aspects can be used to forecast evacuees' behaviour and increase the accuracy of predictions regarding their choices. This information might be used by the emergency engineers when designing emergency paths for new buildings or preparing evacuation plans. Another use is to improve evacuation simulators, helping experts to develop more intelligent and realistic agents.

6.5 The Auditorium Experiment

In this section the results from the Auditorium scenario are presented and deeply analysed.

The expected outcome of this experience is to find out if there is a tendency to get out of an auditorium using the same way to get in instead of using the nearest exit.

6.5.1 Experimental Setup and Sample Characteristics

The auditorium scenario is described thoroughly in Sections 4.4.1 and 5.4.3. This experience was conducted in parallel with the Alarm ID experiment (see Section 6.3).

As explained before on Section 5.4.3, the role play presented to players consists on an auditorium with a certain inclination and entrance at two different levels: upper (near the rear of the auditorium) and lower, near the screen or stage (see Figure 5.15). The game starts with the avatar entering the auditorium using the top or rear entry and sitting at the top row. Meanwhile a siren alarm sounds and the player is urged to leave the auditorium by one of the two possible exits: the top entry leading to the shopping centre or the bottom one, the emergency exit. The experiment is repeat four times for the following combinations: i) using top entry and sitting at top row; ii) using top entry and sitting at bottom row; iii) access through bottom entry and sit at bottom row; iv) enter via same bottom entry and then sitting at top row (see Figure 5.16).

This experiment goal is to find out which is the exit preference for each of these possibilities: if there is a tendency to exit using the same way in, or using the nearest exit.

The scenario presents some challenges to the participants. It is not clear the total length of the path from inside the auditorium until the outside of the building. Both exists / entrances are paths leading to unknown places and unknown length. This is what happens when someone is inside a cinema or an auditorium in a complex multi-floor building such as a great shopping centre. Although the path used to get in is known, normally it is not the fastest and / or safest way to get out. And the emergency exits lead to unknown corridors and stairs.

The population sample is the same as that of the Alarm Id experiment and is characterized in the same section. Similarly to the previous experiments, the sample was divided into two groups, one answering first the questionnaire and playing the game later, and the other in reverse.

6.5.2 Results from the Experiment

Results from both the questionnaire and the SG are presented in Table 6.15. This table contains, for each scenario, the exits selected in absolute values (frequency) and percentage. Comparing the columns corresponding to the SG and the questionnaire, the values are similar. Subjects prefer to use the nearest exit even when they use another entry to get inside the auditorium. Indeed, over 90% of subjects sitting in the bottom row chose the bottom exit. When subjects are sitting in a top row, a percentage ranging from 61% to 82%, depending on which entry they use to get inside, and whether answering to questionnaire or playing the game, chooses the top exit.

Another interesting aspect is that the bottom exit is chosen more often than the top one. In fact 57% of the subjects playing the game and 68% of the respondents prefer to use the bottom exit, even when they are sitting in the top row. Of course, these figures are higher when subjects are sitting near the bottom exit (93% and 95% when playing the game; 96% and 100% when answering the questionnaire).

Table 6.15 – Exits chosen by the participants for each possibility

	Questionnaire				Serious game			
	Top exit		Bottom exit		Top exit		Bottom exit	
Auditorium scenario	**Value**	**%**	**value**	**%**	**Value**	**%**	**value**	**%**
1 - Top entry / Top row	35	61%	22	39%	44	77%	13	23%
2 - Top entry / Bottom row	2	4%	55	96%	4	7%	53	93%
3- Bottom entry / bottom row	0	0%	57	100%	3	5%	54	95%
4 - Bottom entry / Top row	37	65%	20	35%	47	82%	10	18%
Totals		32%		68%		43%		57%

Indeed, the top exit was barely chosen when the subject is seated in bottom row. Although all subjects said they would exit through the bottom entry, when answering the questionnaire, 3 subjects said going up when playing the game (5%).

6.5.3 Association between Serious Games and the Questionnaire

Similarly to previous experiments, a statistical analysis using SPSS was made in order to investigate a possible association between the SG and the questionnaire.

Looking to the statistical results presented in Table 6.16, the Chi-Square test shows no statistical evidences of association between the game options and the questionnaire answers. And the McNemar's test confirms the existence of considerable differences between values in the first and last situation.

Table 6.16 - Association between the game and the questionnaire

Association between	p-value (Chi-Square)	p-value (McNemar)
1 - Top entry / Top row (G1 vs Q1)	0.754 (C)	0.093
2 - Top entry / Bottom row (G2 vs Q2)	0.137 (F)	<0.625
3- Bottom entry / bottom row (G3 vs Q3)	NA	NA
4 - Bottom entry / Top row (G4 vs Q4)	0.141 (F)	0.031

Legend: (C) Chi-Square for independence test with continuity correction; (F) Fisher test; NA - Not applicable.

A deeper analysis was performed by using the two-way frequency cross tabulation tables. Considering that "1" means the upper exit and "2" the lower emergency exit, it is observable that a substantial number of subjects had different results in first and last situation, although when considering globally the SG and questionnaire results are not that different (see Table 6.17). The labels of the tables correspond to each of the four runs of this experiment.

The top left table refers to the first run, when the subject gets into the auditorium using the top entry and seats near the top (T4_G1 stands for the SG and T4_Q1 for questionnaire). Looking to the rows, 44 subjects selected the top exit ("1") and 13 the bottom ("2"). These tables show how many of these selected a different exit when answering the questionnaire (columns "1" and "2" of the same table). So, of the 44 subjects, indeed 16 had selected the lower exit ("2") when answering the questionnaire. And from the 13 subjects that opted to exit through the lower emergency exit ("2"), 7 had preferred otherwise on the questionnaire, answering "1". This means that a total of 7+16=23 subjects changed their responses (40%).

Table 6.17 – Two-way frequency cross tabulation tables for the Auditorium

T4_G1 * T4_Q1 Cross tabulation

Count

		T4_Q1		Total
		1	2	
T4_G1	1	28	16	44
	2	7	6	13
Total		35	22	57

T4_G2 * T4_Q2 Cross tabulation

Count

		T4_Q2		Total
		1	2	
T4_G2	1	1	3	4
	2	1	52	53
Total		2	55	57

T4_G3 * T4_Q3 Cross tabulation

Count

		T4_Q3		Total
		1	2	
T4_G3	1	0	3	3
	2	0	54	54
Total		0	57	57

T4_G4 * T4_Q4 Cross tabulation

Count

		T4_Q4		Total
		1	2	
T4_G4	1	33	14	47
	2	4	6	10
Total		37	20	57

Legend: T4_G1*T4_Q1 – Top entry / Top row (G1 vs Q1); T4_G2*T4_Q – Top entry / Bottom row (G2 vs Q2); T4_G3*T4_Q3 – Bottom entry / bottom row (G3 vs Q3); T4_G4*T4_Q4 – Bottom entry / Top row (G4 vs Q4).

The second table (top right side of Table 6.17) presents the results for the situation when the subject gets in using the top entry but sits near the bottom of the auditorium. In this case, only four subjects changed their responses (1+3=4, 7%).

The third table (bottom left side of Table 6.17) shows the results for the situation when the subject gets in using the lower and sits near the bottom of the auditorium. In this case 3 subjects changed their responses. While all participants said preferring the bottom exit, three playing the game changed their minds and selected going up (5%).

The fourth and last table (bottom right side of Table 6.17) corresponds to the situation when the subject gets in using the lower entry but sits near the top of the auditorium. In this case, a total of 14+4=18 subjects changed their responses (32%).

Table 6.18 – Association between the scenes and gender

	p-value (chi-square)		p-value (McNemar)	
Association between	**Male**	**Female**	**Male**	**Female**
Auditorium G1 vs Q1	0.320 (F)	1 (F)	0.508	0.180
Auditorium G2 vs Q2	NA	0.151 (F)	NA	1
Auditorium G3 vs Q3	NA	NA	NA	NA
Auditorium G4 vs Q4	0.562 (F)	0.322 (F)	0.727	0.021

Legend: (C) Chi-Square for independence test with continuity correction; (F) Fisher test; NA - not applicable.

Looking at Table 6.18 the statistic analysis shows that **the gender has no significant impact on the results**. All the Pearson chi-square test p-values, using Fisher's exact test, are greater than the alpha value (p-values > 0.05). Therefore, the McNemar's test is not relevant, although presented.

Considering **the fire training experience**, the statistic analysis shows **no association between this aspect and the results** (see Table 6.19). Whenever no changes among the questionnaire and the SG occur, the test is not applicable (NA). Since all available chi-square p-values are greater than 0.05, no statistical evidence of association exists and therefore the McNemar's test is not relevant.

Table 6.19 – Association between fire-training experience and the results

	p-value (chi-square)		p-value (McNemar)	
Association between	**Yes**	**No**	**Yes**	**No**
Auditorium G1 vs Q1	0.491	1	1	0.115
Auditorium G2 vs Q2	NA	0.128	NA	1
Auditorium G3 vs Q3	NA	NA	NA	NA
Auditorium G4 vs Q4	NA	0.157	NA	0.077

Legend: (C) Chi-Square for independence test with continuity correction; (F) Fisher test; NA - not applicable.

6.5.4 Qualitative Analysis of the Auditorium Scenario

From the result analysis, subjects prefer the nearest exit and the lower exit, by this order. When asking some subjects to justify their option, the prevalent response was that it is easier and more intuitive to go down than up. And this statement is confirmed by the quantitative analysis. Another aspect, particularly for those using the game, is that the exit sign on top of the lower exit is more visible than the sign showing the top exit. Some subjects (at least four) said that they would favour the lower emergency exit, because the top one leads to the main building entrance, and includes having to go to the lobby, whilst the bottom exit should lead to a safer place; or at least they thought so. Meanwhile, three subjects decided to go up when playing the game, after getting in using the lower entry and seated in the lower row; when asked about these unexpected option, their responses where evasive and no rational reason was given.

6.5.5 Conclusions from the Auditorium Scenario Experiment

This test aims to find if people in general, when inside an auditorium, tend to use the nearest exit or the same exit they use to get inside. Another important aspect is related to whether people exit selection depends on the relative location where they are sitting, particularly the ones further away from the entry they use.

Looking deeper to the results and comparing them with the help of the graphical plots (see Figure 6.3). The statistical analysis shows that, although apparently both the questionnaire and the SG have similar results, there is no direct association between them. And when analysing using other parameters, such as gender and fire expertise, no significant association is found either. This fact leads to conclude that using questionnaires or virtual environments might bias the results. Another possible explanation is that subjects tend to change their answers to the same question or scenario, leading to unpredictability of human behaviour and decision-making process.

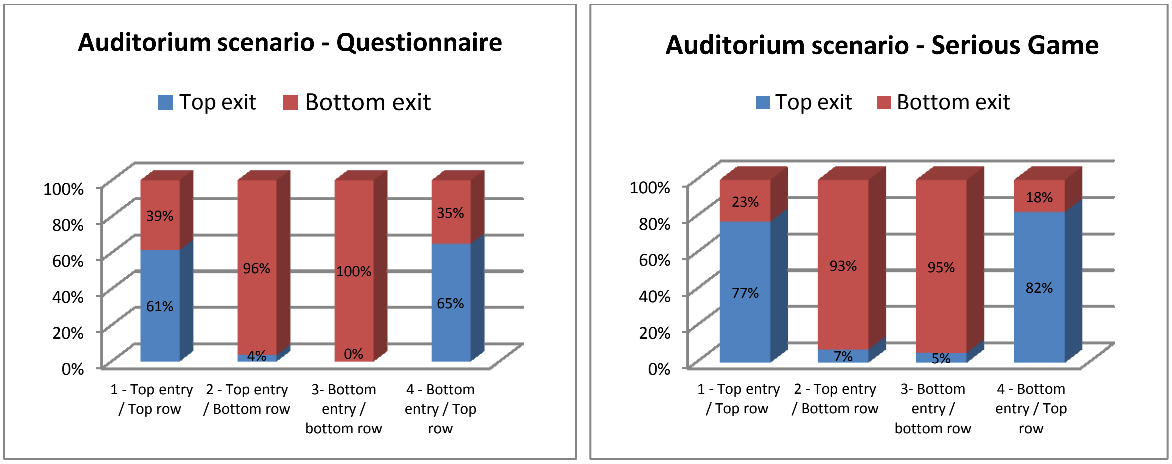


Figure 6.3 - Graphical plot of the results for the Auditorium (questionnaire and SG)

But when considering globally the aggregate values, the results are quite similar, and a trend can be made from the results. In fact, subjects prefer the nearest exit (the worse case is 61%). And the SG has better results in this comparison with questionnaire when the player sits at top rows (77% versus 61% when get in using the top entry; 82% versus 65% when get is using the bottom entry). The other interesting aspect is that the bottom exit is chosen oftener than the one on the top (over 90% when sitting near the bottom; 57% of the subjects playing the game and 68% of the respondents when they are sitting at the top row).

These tendencies might help emergency planners and safety experts when designing evacuation strategies for spaces similar to this one. They can be used as well to improve evacuation simulators by incorporating intelligent agents mimicking behaviours elicited from real persons.

6.6 Summary

The experiments carried out and presented in this chapter allow some interesting conclusions to be drawn.

First, the experimental setup designed for human behaviour elicitation using questionnaires and the SG concept, an instantiation of the SPEED methodology, has resulted in a collection of data that can be further used for improving existing pedestrian simulators. The main goal was to implement a set of experiments using SG in the specific domain of evacuation scenarios. These scenarios include correct alarm identification; the way-finding process when exiting from an unknown place, facing some adverse situations such as smoke, fire and people running on the opposite direction of the emergency signage; and at last which exit to choose when having to leave rapidly an auditorium: the nearest one or the same way used to get in. This preliminary set of experiments, designed with the help of an expert panel, and improved using a methodology based on the Delphi method, can be further expanded to include other scenarios and experiments.

Despite some differences found, among the responses using either the questionnaire or the SG, some tendencies can be found, such as the tendency that pedestrians show when preferring to go right than left, when no indication on the direction to take is available. The reaction of subjects when facing smoke or fire can give fire researchers valuable information. Whereas fire is impassable, smoke may or may not be. Even though the emergency signage points towards the smoke or fire direction, evacuees have to decide whether they follow that indication or go elsewhere. More interesting is the situation when people are running on the opposite direction of the emergency signs. And this methodology can be used for further test other scenarios and hypothesis.

Another conclusion from the analysis of the experiments carried out, is that subjects behave differently when answering a questionnaire or playing a game. The statistical analysis carried out did not find strong evidences of association between the results collected using the questionnaire and the SG. The immersion nature of the SG affects the perception of the scenario, and this might be one of the explanations for these results. It became clear that human behaviour is not constant and varies according to other aspects that these experiments were not able to show. Although aspects such as gender, fire training, and even psychological dimensions were explored, using statistical tests, the associations found are scarce and insufficient to support a sound theory. Due to the limited scope of the experiments designed, no further analyses were possible at this stage.

However, these results are not as deceptive as they might seem at a first glance. They illustrate that the human decision making process is very complex and not as straightforward as expected in order to be used by pedestrian simulators. The randomness related to humans reactions and behaviours leads to the need of further research looking for other ways to elicit human behaviour.

The comparison of the results between the questionnaire and the SG, demonstrates that, at least for the experiments and sample presented, they should be taken cautiously because the shifts in the responses is too high and suggest that subjects do not always proceed in the same way, for there is a random aspect that still needs to be quantified.

Nevertheless, the confirmation of the unpredictability of humans' response in such limited scenarios with a small number of possibilities of choice (binary: going up or down, left or right), can shed light upon the cautions that researchers must have when using pedestrian simulators to mimic human behaviours in scenarios, such as the ones presented. Some tendencies in the scenarios described previously may be used to improve existing simulators, since some real data was acquired and can be used for steering intelligent agents during their path towards an exit. Combining the elicited data with the PDA concept, as described thoroughly in chapter 4 (see Section 4.3), as conceived in the SPEED methodology, an iterative process can be implemented, using subjects performing the experiments to improve the collected data. This simulation technique, known as "human-in-the-loop", is the basis to implement intelligent agents using the PDA concept, and the core of the SPEED.

These aspects are of paramount importance for both fire safety engineers and researchers. Forecasting how people will behave during the evacuation process might help stakeholders to take preventive actions in order to avoid risky situations, such as herding behaviours leading to clogging exits. The elicited knowledge on human behaviour can help architects and engineers at the design of safer buildings, by using the tendencies found to improve the layout of buildings.

Other scenarios can me envisaged to meet particular situations, following the methodological approach described herein. A collection of scenarios typically present in evacuation situations can be then used for elicitation of behaviours, to further improve the behavioural data that is so much needed in this field of expertise.

Meanwhile, the games built for the aforementioned purpose can be used as well for training and education, an important aspect that is of great importance. Ultimately, the aim of this research is to find ways and strategies leading to safer behaviours that can save lives in the future.

7. Conclusion and Final Discussion

It was from the very beginning of this thesis research that behavioural modelling and elicitation of human behaviour were targeted. The problem of capturing and synthesizing human behaviour by means of behavioural modelling is a challenge for Artificial Intelligence researchers (Tweedale, 2013). Known approaches to tackle this issue include the Belief-Desire-Intention (BDI) architectures combining modal and temporal logics as the basis for agent planning and action selection (Macal and North, 2010; Wooldridge, 2002).

New elicitation methods of human behaviour will ultimately provide simulations mimicking humans with better and more realistic behavioural models. Applications are varied and include all kinds of social simulations. As a case study, the behaviour of pedestrians when searching the best path to exit from a building was chosen. This area of research, often called building egress, or evacuation, has gained increasing interest by the research community, with important implications to architecture and building management.

This final chapter reveals the contributions and main achievements of this thesis. This is followed by the presentation of on-going research on the implementation of the PDA concept based on the behaviour elicitation phase devised for the SPEED framework. This is expected to close the framework's main iteration loop. This chapter concludes with suggestions for further developments, future work and shares some of the important lessons learned.

7.1 Contributions and Main Achievements

The main contribution of this thesis, from a scientific point of view, is the conceptualisation of the SPEED methodology. The novelty of the SPEED approach consists in using SGs combined with stated-preference questionnaires, in which virtual worlds are created to provide players with an immersive environment and thus recreate typical scenarios in which customary behaviours can be elicited.

The SPEED framework uses SGs, a cheaper and more efficient technology when compared with other complex and expensive high-fidelity simulators (e.g. CAVEs) to reveal the decisional processes behind the actions people perform when living and interacting in the real world. Rather than merely collecting data, by using the intrinsic nature of SGs, it is possible to create a library of experiments and scenarios, impelling the player to take a sequence of actions from which the semantics of each decision can be elicited. Such knowledge can shape the features and idiosyncrasies of intelligent agents mimicking real subjects upon which they are modelled. This process is known as peer-designed agents (PDA), a concept that has emerged recently within the AI community and is still in its infancy. The complete SPEED framework integrates social simulation, based on SGs for behaviour elicitation, with agent-based modelling using PDA, so as to produce more reliable and representative simulations.

The framework, as conceived, will allow to setup virtual worlds in which artificial societies grow and breed, replicating the real-world ecosystem, where scientists, practitioners and decision-makers can simulate extreme situations. This would otherwise be impossible to test in real life, similarly of using real people as *guinea pigs*. This *in silico* environment can be used for performing what-if analysis in a multitude of scenarios and domains using social simulation.

The *leit motiv* leading to the development of SPEED is related to the urgent need of having simulation tools that are able to help safety engineers and emergency planners, predict the evolution of emergency situations, forecast damages, casualties and test strategies to mitigate such events, if preventing them is not at all possible. Existing simulators, particularly the ones related to evacuation, thoroughly analysed in Section 3.2, still lack a higher degree of realism, much depending on better knowledge of behavioural aspects related to the human decision-making processes, enabling those simulators to produce results reliable enough to be used by stakeholders.

Bearing in mind the aforementioned aspects, SPEED turns out to be a framework that might be used in other social simulation domains, where pedestrian behaviours is required. These include not only evacuation scenarios, but other indoor and outdoor situations, as previously discussed in Section 2.4, including planning and managing complex buildings, multi-modal transportation systems and other situations requiring pedestrian simulation.

This thesis, besides the SPEED Conceptualisation, describes a partial implementation of the framework using SGs applied to evacuation scenarios. While SPEED's complete implementation is a major undertaking, the results achieved present great potential for further research, including other Ph.D. thesis, one of which is already in progress, having this thesis as a starting point.

From the technological point of view, the experimental setup, having successfully tested some scenarios, can be used as an example for the creation of a library containing a set of typical situations found in evacuations or other domains. This may have the ability to serve as an aid to support behaviour elicitation by inferring behaviour patterns from the analysis of player's logs during the game sessions. The mock-up scenarios presented serve as a test-bed to demonstrate the viability of the concept.

As for the applied perspective, this thesis main contribution consists in using SGs as a cheaper and rapid-prototyping tool complementary to the traditional questionnaires that are used for the elicitation of pedestrians' behaviour. Another important aspect to highlight is the virtual environment using 3D models imported from existing buildings, that combined with the library of scenarios referred in the preceding paragraph, might be used as a training tool to replace, if not totally at least in part and complementarily, real-world fire drills. The proposed approach thus represents a cheaper and more practical alternative to expensive and infrastructure-dependent traditional approaches.

Research questions were identified and hypotheses were raised (see 1.4.2 and 1.4.3), after a literature review of concepts related to the domain, including the background knowledge of all areas needed in this research (see Chapter 2) combined with an investigation of related work (see Chapter 3).

For the research question:

> RQ1. *To which extent are responses to questionnaires related to the actual behaviour of the subject while playing the game?*

And related hypothesis:

> H1: *SGs are valid means for data collection of human behaviour, complementary to questionnaires*.

The traditional use of stated-preference questionnaires presented to subjects sometime after the simulated or real evacuation are biased since they rely on the memory of participants. SGs can therefore present an immersive environment recreating the situations for which the questions are related.

The experiments envisaged, designed with the help of the expert panel inspired by the Delphi method, show that there is evidence of an association between the results of the game and of the questionnaire in some scenarios. However a detailed analysis shows that a percentage of subjects change their options from the questionnaire to the SG and vice-versa. One possible explanation is that human behaviour is not constant and changes depending on many circumstances, such as the environment, the mood and others aspects. Only a deep study involving sociologists and psychologist could eventually find with a greater detail the reasoning principles driving human behaviour in scenarios as those implemented in this thesis. In conclusion, the use of questionnaires for data collection must be taken carefully, since data might be biased. SGs are therefore a promising means for complementing questionnaires helping the social scientists to enhance the experiments and foster the quality of the data to be collected.

For the research question:

> RQ2. *To which extent can SGs be used as a behaviour elicitation tool?*

And related hypothesis:

> H2. *SGs are a valid means for behaviour elicitation.*

The data resulting from the experiments regarding human behaviour is of great importance for evacuation simulators modellers, to improve the validity of their what-if simulations. One of the major critics to the use of evacuation simulators for evaluating the egress paths of existing or new buildings is precisely related to the lack of human behavioural data and reliability of the intelligent agents trying to mimic humans.

The data collected using the EVA experiments, for different age groups and with a wider sample within the SPEED framework, can reveal new knowledge of humans' behaviour when evacuating buildings. The novelty of the SPEED approach on the use of SGs consists in creating virtual worlds providing players with an immersive environment in which typical behaviours can be elicited. The complex and sometimes not evident decision-making processes of humans can therefore be elicited by social scientists. Using a library of scenarios carefully designed to expose subjects' behaviours and the ways of thinking during the decision-making process are consequently a major tool for the social scientists pursuing techniques for behavioural modelling.

For the research question:

> RQ3. *How can data collected through SGs be effectively used to breed and grow artificial societies in agent-based crowd simulators?*

And related hypothesis:

> H3. *Data collected through SGs can be used to breed and grow artificial societies in agent-based simulators, leveraging the implementation of the PDA concept.*

Some experiments with social simulation using NetLogo, where the agents were modelled using the data collected with the SG, consisted of a preliminary implementation of the PDA concept. The PDA aim is to have intelligent agents designed by their peers. This research and concept applied to evacuation simulators combined with SGs, consists of a novel approach for which no preliminary work exists (Almeida et al., 2014a, 2014c, 2014d). The early experiments using the elicited knowledge for implementing the PDA concept are the basis for the research conducted by Valerio Zamboni from Milano-Bicocca University, supervised by Prof. Vizzari, and presented briefly in the following section. From these experiments it is indeed possible to conclude that data collected by means of SGs can be used to breed and grow artificial societies in agent-based crowd simulators, leveraging the implementation of the PDA concept.

In conclusion, the use of SGs for behaviour elicitation, complementarily to traditional methods such as questionnaires, paves the way for the use of this tool as a means for devising and implementing more reliable and credible intelligent agents. This approach presents enormous potential to be used in many domains, such as pedestrian simulations, particularly, in evacuation scenarios.

Additionally, virtual environments can be used by emergency planners and other stakeholders, to train and educate people by means of using SGs as a virtual fire drill, thus complementing traditional ways. This approach implies that fire safety experts conceive the scenarios accordingly so that the SG setup can be properly customized.

Finally, the concepts of behaviour assimilation and persuasion, as coined by (Rossetti et al., 2013), are addressed by the SPEED methodology, although further development is needed.

7.2 Closing the loop: PDA

The implementation of the SPEED framework, as devised in the methodological approach (see Section 4.3) consists of three phases: i) data collection; ii) data mining; and iii) peer-designed agents (PDA). After data collection using SGs, the last phase relies on allowing ways to synthesize realistic populations for agent-based simulations, using the data obtained from the previous phases (see Figure 7.1).

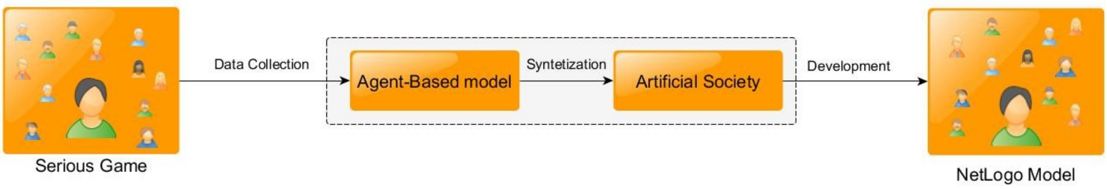


Figure 7.1 – SPEED first class instantiation using SGs and NetLogo

The concept of PDA consists in creating agent-based models, as realistically as possible, aiming to recreate intelligent agents trying to mimic real persons, based on data and knowledge elicited from the entities they will imitate. These computational agents are developed by humans as delegates of people (Chalamish et al., 2013). The design of such agents is expected to be developed by non-experts; the main premise thus resides in having agents programmed to reflect to a certain extent, the behaviour used by the peers they use as role-model (Elmalech and Sarne, 2014).

The original concept leverages on the assumption that PDA-based models "*capture people's behaviour adequately, and therefore a PDA-based system is likely to perform similarly*" to the case the system is emulating (Elmalech and Sarne, 2012). Such a rather novel concept has its roots in the research made by (Grosz et al., 2004) using human-in-the-loop experiments combining humans and agents in cooperative behaviour for a variety of decision-making strategies using social games. Social simulation experiences on cooperative relationships were further addressed (Talman et al., 2005).

Using the application domain of building evacuation, a PDA-based system can be developed using the elicited knowledge from the experiments described earlier in Chapters 5 and 6, in order to design more realistic agents. Indeed, such endeavour is underway at LIACC. An international master's student from Milano-Biccoca University, Valerio Zamboni, has developed preliminary experiments implementing an agent-based evacuation simulator using NetLogo to demonstrate this very aspect of the SPEED methodology.

NetLogo is an agent-based simulation framework that permits to quickly create social simulation prototypes. It uses the cellular automata concept (Neumann, 1966) and is particularly suited for testing ABM techniques to build artificial laboratories for experimentation *in silico* (Kokkinogenis et al., 2013). In NetLogo the cells are called "patches" and the agents are "turtles", although the patches are treated as agents too (Gilbert and Troitzsch, 2005). Using the example described earlier in Section 3.6.3, developed by (Ribeiro et al., 2012b; Ribeiro, 2012), a simulation of building "I" at FEUP, on Asprela campus, first floor (see Figure 3.12) was implemented in NetLogo.

Figure 7.2 – NetLogo simulator user interface showing the plan of the 1st floor of "I" building at FEUP

Individual agents are modelled as having a given probability of executing specific actions (e.g. following people running, turning right or left, going through smoke, etc.). The short term goal is to construct realistic agents using the data we obtained from the questionnaires/game, in combination with secondary information such as demographics (e.g. age, gender, education) in such way that, for example, it is possible to instantiate a whole school using data from only a small sample of that school's population.

Considering that there are different personalities and groups, one possible way of representing them is by splitting the population into different groups and categorizing them independently. This can be achieved in a number of ways including the use of clustering algorithms, such as k-means or nearest neighbour. Using this approach, it is possible to have a large simulation of many hundreds or thousands of agents recreating an actual building or facility, but having only a few dozen of common behaviour groups. This data-driven approach to group the different humans according to their reactions is a considerable contribution on its own, and might be achieved by categorising the data collected using the questionnaires and the SGs. Nevertheless some cautions must be taken because the sample may not be representative of the entire population, in which case appropriate analysis to guarantee representativeness must be carried out.

Extrapolating from demographic information to user actions, it is possible to construct a rule-based system in which, for each agent instance, the corresponding probability for each feature is assigned (as depicted in Figure 7.3).

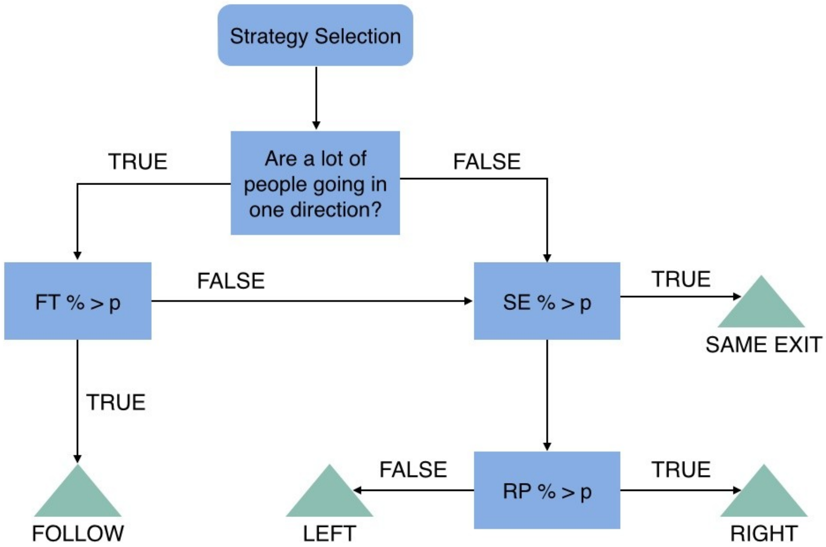


Figure 7.3 – Decision-making process for PDAs based on following others tendency (FT), use the same exit (SE) and right preference (RE).

When the agent has not enough knowledge to select the best exit, they will try to apply some strategies, depending on personality traits. The main factors that will guide them through the decision-making process are: i) the tendency to follow others (Following Tendency - FT); ii) the tendency to use the same entry as the exit (Same Exit tendency - SE); iii) the tendency to turn right (Right Preference - RP).

The rule-based system starts by testing if there is a considerable amount of people going in one direction (at least three agents going in the same direction). If that is true, a random generated number p is compared against that agent's tendency to follow others (FT). If this p value is lower than FT then the agent follows the other agents, otherwise it tests this agent's tendency to exit using the same way in (SE). Again, if the p random number is lower than SE, the agent will exit through the same way used to get in; otherwise, the p value is compared with the agent's tendency to turn right (RP). If the p value is lower than RP, the agent will turn right, otherwise it will turn left.

The main goal of this technique is to have a credible evacuation simulator mimicking human behaviour in the best way possible. Using the sample features, collected from the experiments described in Chapter 6, namely the exit-choice and the auditorium experiments, some clustering was made resulting in the decision-making flow-chart presented. The ongoing research consists in having a test-bed for evaluating the PDA approach.

7.3 Future Work

Looking closer at what can be done to move further the knowledge regarding how to model and simulate human behaviour in emergency situations, using the SPEED methodology, some ideas arise:

- Expanding the evacuation scenarios to include other options and different layouts.
- Increasing the complexity of the game by allowing the player to use extinguishing systems, such as a portable extinguisher or a fire hose.
- Developing other scenarios in addition to buildings, including outdoor scenarios as well.
- Applying the SPEED methodology to the elicitation of pedestrian behaviours in other situations beside evacuation scenarios, such as using multi-modal transports or when shopping.
- Automating data collection and analysis, in order to interconnect with the agent-based simulator (using either the NetLogo approach or another custom-designed simulator) and close the loop, as described earlier on 7.2.

SGs are also used for training and education. When considering the Serious Games approach, there is a multitude of future works that can be done just by adding new features to the scenarios already developed:

- Using SGs to train and complement real fire drills in sites where it is difficult to perform them, such as hospitals, elderly care centres; this way, complex situations such as fire at the emergency room or at the operating theatre, could be trained and strategies on how to deal with such extreme conditions might be tested without harming or harassing anyone.
- Having SG to train occupants at hotels: during the check-in the client would play the evacuation game to get acquainted with the fire exits and how to alert the reception (many hotel customers do not know how to call the reception using the internal telephone).
- Employing the gamification concept to engage participants into developing their skills while learning and training safety aspects.

By using the SG platform already developed, it can be expanded to include other features such as:

- Implementing multi-player scenarios, following the preliminary work by (Oliveira et al., 2015).

- Creating an add-on to automatically import CAD or BIM files into the SG.
- Having different non-playable characters (NPCs) in the scenarios, each representing different roles. For instance, having people with disabilities, children or elderly adults should cause different reactions on players: what would the player do if an elderly person fainted onto the floor? Preliminary work is underway (Almeida et al., 2015).
- Using the web deployment facility of Unity3D for creating participatory simulations and massive data collection.
- Registering the amount of time the player has been subjected to smoke and even fire, would make the simulation closer to the real world. Dying states and animations would be implemented to show that the user failed to escape. This situation would hopefully cause more stress to the individuals being tested, as it happens in real life. By integrating data from fire dynamic simulator (FDS), the smoke and temperature can recreate vivid scenarios.

The aforementioned ideas and research development directions consist of a rich set of possibilities to extend this thesis and stem other research projects. The final goal is to foster the development of the next generation of pedestrian simulators using the PDA concept.

7.4 Lessons Learned

The study of human behaviour is of paramount importance for the development of realistic and valid simulators in a variety of domains, including crowd behaviour and in particular the evacuation of buildings. Models with agents mimicking the human behaviour and decision-making process are much dependent on having good knowledge of those mechanisms. There are no easy or definitive solutions so far and much research has been done pursuing this goal (Carattin and Brannigan, 2013; Galea, 2012).

The use of SGs is a cheaper way to leverage the elicitation of human behaviour. Comparing it with the traditional questionnaires, SGs present similar results with the additional benefits of providing more realistic scenarios, immersion feeling to subjects using the concepts coined as **behaviour elicitation**, **behaviour assimilation** and **behaviour persuasion**.

However, the development of such SG creating VR vivid environments, despite the vast advances in the areas of computer graphics, animation and human computer interfaces, **a great effort is still needed to easily and straightforwardly implement a virtual fire drill scenario directly using**

the architectural blueprints. This is basically because 1) most of the architectural drawings are in 2D and the conversion process to 3D is costly and time consuming, and 2) even when the 3D architectural models are available (typically designed using Revit or AutoCAD) they need to be converted to a file format recognizable by the game engine. And afterwards, 3D scenarios must be customized in order to present a realistic feeling to players. Furniture and graphical environment aspects need to be added. Features such as character animation, sounds and special effects (for instance fire and smoke) require programming and the use of add-ons with a high degree of complexity.

Then, the data collection process must be carefully planned and implemented. The co-validation process has revealed unexpected aspects that were not considered initially. Combining such different means to elicit knowledge, questionnaires and videogames, poses challenges that require some ingenious efforts to overtaken. One of the scenarios had so many complex aspects that were left out of the experiments. This was also due to the many hundreds hours of trial-and-error work needed for the implementation process, resulting in a rather disappointing outcome.

Publications and presentation of the work-in-progress at conferences (see full list at Appendix E) have shown that other researchers are interested and even curious about the methodological approach devised and its results. This attempt at using videogames, in the “serious games” way, to collect data concerning human behaviour, although tried before by others, has still a long way to go and evolve. Not only in the specific domain of fire safety and building evacuation, but related to other fields such as pedestrian movement, driving behaviours, and social interactions in general.

In respect to the results obtained, the data analysis of the experiments evidenced a statistical association between the questionnaires and the SGs for some of the situations and scenarios. However, when looking deeper into the data a percentage of subjects change their options from the questionnaire to the SG and vice-versa. Therefore, the main conclusion of these facts is that **questionnaires and SGs may be complementary but not mutually exclusive**. An additional aspect is that **some of the subjects tend to change their behaviours, making it hard to create models that can replicate, with a great degree of certainty, human behaviour.**

The data collected can be further used to feed and breed artificial societies in a continuous and iterative process, using the methodological approach presented in Section 4.2 named SPEED. This issue is of great importance for the ABMS community and the AI in general, besides the specific domain of the fire safety, in a way that pursuing models that mimic the human behaviour is an endeavour with many challenges and a long way ahead.

The lessons learned from the related experiments, and the various attempts made in order to model and capture pedestrian behaviours so as to implement proper evacuation simulators, were:

1. The UWB approach for human trajectory extraction (see Section 3.6.2 and Appendix D), although it seems a viable approach for microscopic pedestrian analysis, it needs further research for human behaviour elicitation.
2. Unity3D proved to be a valuable framework for videogame development, and cumulatively for the creation of vivid and realistic 3D environments.
3. Additionally, Unity3D provides features that proved to be useful for human behaviour elicitation: the web deployment capability, the rapid prototyping and the multi-player capability.
4. Modelling the 3D scenarios is a complex, fastidious and laborious task, for which automation tools are needed; otherwise it makes the SG development process too lengthy and expensive.
5. The overall concept of using SG recreating realistic 3D environments and immersive VR scenarios has proved to be a valid means for both human behaviour elicitation and training, being possibly a good alternative or complementary tool to the traditional fire drills.
6. NetLogo can be used for the implementation of the PDA concept, to underlie the agent-based component of the SPEED framework.

Perhaps the hardest lesson was that **the development of such a huge endeavour,** as it was envisaged during the research made for this thesis, **requires a wide team of experts from different areas**. A multidisciplinary team is needed for a better usage of the potential of SPEED, composed of game designers, game programmers, social scientists such as sociologists and psychologists, statisticians and artificial intelligence experts. Besides these, field domain specialists are needed as well, to prepare the scenarios, evaluate and interpret the results.

7.5 Final Remarks

Behavioural modelling of humans is a big challenge, and this thesis presents a step forward in the direction of pursuing a way to address such an issue, with the conceptualisation of the SPEED methodology. Albeit the SPEED project is a wider methodological framework beyond the scope of this PhD, it very well represents the great potential for generating further research having this thesis as a starting point.

Additional contributions have naturally arisen from this research work, representing opportunities for further investigation and practical applications of the implemented test-bed. It is important to stress the fact that human behaviour modelling is a challenge that will be the focus of many researchers in the future.

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Appendices

For a better understanding of this dissertation, some important material used during the research is presented in appendices. This way the reader looking forward to better understand all the methodological tools used is guided to this part of the document, leaving the main sections with less text and without information that is not fundamental to the understanding of the dissertation, but rather complements it.

Appendix A has the questionnaire presented to the expert panel.

Appendix B contains a short biography of the experts that made part of the expert panel.

Appendix C shows the tables with results from the expert panel questionnaire, aggregated by sections.

Appendix D holds more data and results concerning the experiments made using UWB for pedestrians' trajectory extraction.

Appendix E consists of an exhaustive list of publications, conferences attended and media exposure of the research done during the time that the present dissertation occurred.

Appendix A

Questionnaire presented to the expert panel.

Pilot Test

Questionnaire and Serious Game: questions and scenarios

The following questionnaire has four sections, in each one there is (at least) one text box like this:

Expert Panel evaluation chart

The expert shall classify each one of the questions using the scale (1-5):

1-totally disagree; 2-disagree; 3-neither agree nor disagree; 4-agree; 5-totally agree.

In some cases, specific questions are made.

There is also a column for additional commentaries, such as rephrasing the question.

Section III is not to be evaluated (included here just for your knowledge).

Please do not answer the questionnaire, only the evaluation chart!

If you have any doubts, please do not hesitate, e-mail me at: joao.emilio.almeida@fe.up.pt.

Thank You very much for your precious time and invaluable help!

João Emílio Almeida.

I – Subject general characterization *(don't answer!)*

1. **Age: __**
2. **Gender: __ (M/F)**
3. **Dominant hand:__ (Right-handed / Left-handed / Ambidextrous)**
4. **Educational qualification –** grammar school (up to 4th grade); up to 6th grade; up to 9th grade; up to 12th/professional course; Bachelor degree; Master degree; PhD)
5. **Profession:___________________**
6. **Do you have experience as a user of computers? Y/N** (*basic computer skills*)
7. **Do you have you experience with videogames? Y/N** (use of computers for gaming)

Expert Panel evaluation chart:

Question	Evaluation (scale 1-5)	If you do not agree or have other suggestions please rephrase the question (or write your comments here)
1. Age		
2. Sex		
3. Dominant hand		
4. Literacy		
5. Profession		
6. IT experience		
7. Videogames experience		

Please note: scale 1-5 (1-totally disagree; 2-disagree; 3-neither agree nor disagree; 4-agree; 5-totally agree)

Do you have any other question to add to this section of the questionnaire?

If so, please write it here:

____

II – Characteristics of the subject regarding fire safety knowledge *(don't answer!)*

1. **Do you have any training on Fire Safety?** (Y/N)
2. **If so, in what areas** (you may choose more than one):
   a) portable extinguishers use;
   b) fire hose use;
   c) egress / evacuation;
   d) general fire safety concepts;
   e) other? ______________________
3. **If so, what is the frequency of such training** (select only one answer which is closer to your training frequency):
   a) just once;
   b) annually;
   c) every two years;
   d) other; which? _________________
4. **Do you have any previous fire-related experience? (Y/N)**
   (please note: only buildings' fire! Forest or other outdoor fires are not in the scope of this study)
5. **If so, where** (you may choose more than one):
   a) home (yours or someone else's)
   b) workplace
   c) other; which? ______________________
6. **If so, what did you do?** (select all that apply):
   a) fought the fire using a portable extinguisher;
   b) fought the fire using a fire blanket or a wet cloth;
   c) fought the fire using a fire hose;
   d) managed to extinguish the fire;
   e) evacuated immediately;
   f) evacuated only after having tried to extinguish the fire;
   g) left the pace having closed the doors behind you;
   h) called fire fighters or 112 / 911;
   i) called someone to warn about the fire (manager, place owner, colleagues…);
   j) warned other building occupants;
   l) panicked;
   m) stayed calm;
   n) before exiting you took your personal belongings (keys, jacket, mobile phone, briefcase, wallet…)
   o) felt or saw fire (flames)
   p) felt or saw smoke
7. **Do you think you would behave differently facing a fire at a building you know well (e.g. home/office) as opposed to visiting a site that you are not familiar with? (Y/N)**
8. **Do you think that the activity you are doing would interfere with your behaviour to the fire alarm?**
   a) yes
   b) no
   c) I don't know

Expert Panel evaluation chart:

Question	Evaluation (scale 1-5)	If you do not agree or have other suggestions please rephrase the question (or write your comments here)
1. Training on fire safety		
2. Areas		
3. Frequency		
4. Have you ever faced a fire?		
5. Where?		
6. What have you done?		
7. Behaviour regarding familiar location opposed to not known location		
8. Activity has an influence on fire alarm reaction		

Please note: scale 1-5 (1-totally disagree; 2-disagree; 3-neither agree nor disagree; 4-agree; 5-totally agree)

Do you have any other question to add to this section of the questionnaire?

If so, please write it here:

____

III – Subject psychological / behavioural profile

Test to establish the psychological / behavioural profile of the subject (e.g. leadership, courage, resilience, decision making under stress...) and identify some clustering groups (just a few, no more than 5 or 6).

The psychological profile of subjects is considered an important aspect that must be taken into account when assessing their behaviour. For this purpose, a psychological test, namely the 16 PF-5, will be used to characterize the participants. The aim is to find if there is any association between the psychological dimensions and the tendencies, such as turning left or right at intersections or following others.

Not to be evaluated by the expert panel.

IV – QUESTIONNAIRE vs. SERIOUS GAME

Please note:

Each subject will answer the questionnaire (previous sections, I, II and III) as well as the following section with questions related to the various scenarios.

After sometime (between a week and a month), the subject will play the videogame specially conceived for this test in which the same scenarios in the questionnaire will be used. Results from the game, which will save the subject reactions and selections when facing the scenarios will later be compared with the answers given previously at the questionnaire. Data acquired will also be analysed statistically. The goal is to validate the questionnaire using the game.

1st Scenario – Fire alarm sound recognition

Goal: assess subject perception towards a fire alarm sound: if they recognize it; if they think they will recognize and then fail later on; if they do not recognize at all. Perceive the reaction towards the most common alarm sounds and if the fire alarm sound is perceived as different and recognized from others.

A) Questionnaire:

1. Do you think you can recognize the fire alarm sound if you hear it in a building? (Y/N)
2. Can you recognize the following alarm sounds?
   a) Fire alarm (Y/N)
   b) Robbery/intrusion alarm (Y/N)
   c) Emergency vehicle (Y/N)
   d) Fire engine truck (Y/N)

B) Videogame: Scenario where a fire alarm sound is audible; different alarm sounds will be heard and for each the player will be asked if he/she recognizes it and which type it is (fire/robbery/alarm vehicle/fire engine).

For instance: during the game, whilst the subject is performing some duty, such as wondering around searching for something or watching a movie; an alarm sound is played (random one) and the player must answer which type of alarm is.

Possibilities:

a) Ask the subject which one of the four possible alarm sounds it is (fire; robbery/intrusion; emergency vehicle; fire engine); player selects one of the 4 options;
b) Ask the subject which alarm sound does he think it is and have them write it (free text)

Game stores the option and returns to what was going on (while silencing the alarm sound). After sometime, another alarm sounds and new question to the subject is presented. Repeat four times, one for each alarm sound in the questionnaire.

Expert Panel evaluation chart:

Question	**Evaluation** **(scale 1-5)**	**If you do not agree or have other suggestions please rephrase the question (or write your comments here)**
QUESTIONAIRE		
1. Can you identify the fire alarm sound? (Y/N)		
2. Can you recognize the following alarm sounds?		
a) Fire alarm (Y/N)		
b) Robbery/intrusion alarm (Y/N)		
c) Emergency vehicle (Y/N)		
d) Fire engine truck (Y/N)		
VIDEOGAME		
Do you agree with the scenario?		
Which one is best: a) The subject selects one of the 4 possible alarm sounds		
b) The player has to write which type of alarm was heard (free text)		

Please note: scale 1-5 (1-totally disagree; 2-disagree; 3-neither agree nor disagree; 4-agree; 5-totally agree)

Do you have any other question to add to this section of the questionnaire?

If so, please write it here:

____

2nd Scenario – Fire alarm reaction

Goal: assess if the activity the subject is performing has any impact on the fire alarm reaction (pre-evacuation actions).

A) Questionnaire (variant 1):

1. Imagine that you are at home (watching TV or cooking, for instance), in the movies, or at a class and suddenly the fire alarm sounds, what do you do? (select all that apply):

    a) Keep on doing the same activity: __ (write priority option; 0=option not selected)
    b) Call someone (close family, friends): __
    c) Try to warn neighbours/other family/colleagues, about the fire: __
    d) Call the firemen: __
    e) Call 112/911: __
    f) Search the fire location: __
    g) Try to fight the fire using a portable fire extinguisher: __
    h) Try to fight the fire using a fire blanket or a wet cloth: __
    i) Try to fight the fire using water using a bucket: __
    j) Abandon the place immediately without trying to fight the fire: __
    k) Abandon the place only after trying to fight the fire: __
    l) Look for other persons (family / friends): __
    m) Close the doors behind you when leaving the building: __
    n) Panicked: __
    o) Stay calm: __
    p) Other. Which?:____

    Select the options indicating the order of priority 1,2,3,.. (0=option not selected)

Expert Panel evaluation chart:

2nd SCENARIO– variant 1 **Fire alarm reaction – questionnaire**	**Evaluation** **(scale 1-5)**	**If you do not agree or have other suggestions please rephrase the question (or write your comments here)**
Question 1		
a) Keep on doing the same activity		
b) Call someone (closed family, friends)		
c) Try to warn neighbours /other family/colleagues, warning about the fire		
d) Call the firemen		
e) Call 112/911		
f) Search the fire location		
g) Try to fight the fire using the portable fire extinguisher		
h) Try to fight the fire using the portable fire blanket or a wet cloth		
i) Try to fight the fire using water using a bucket		
j) Abandon the place immediately without trying to fight the fire		
k) Abandon the place only after trying to fight the fire		
l) Look for other persons (family / friends)		
m) Close the doors behind you when leaving the building		
n) Panicked		
o) Stay calm		
p) Other; which		
Do you have any other question to add to the questionnaire?	****	

<u>Please note</u>: scale 1-5 (1-totally disagree; 2-disagree; 3-neither agree nor disagree; 4-agree; 5-totally agree)

A) Questionnaire: (variant in which the same questions vary accordingly various locations and activities: home, school, job, cinema, shopping).

Another possibility is to ask the above but for different situations: Home, School, Office, Cinema, Shopping/Leisure.

Action	Home	School	Office	Cinema	Shopping
a) Keep on doing the same activity					
b) Call someone (closed family, friends)					
c) Try to warn neighbours /other family/colleagues, warning about the fire					
d) Call the firemen					
e) Call 112/911					
f) Search the fire location					
g) Try to fight the fire using the portable fire extinguisher					
h) Try to fight the fire using the portable fire blanket or a wet cloth					
i) Try to fight the fire using water using a bucket					
j) Abandon the place immediately without trying to fight the fire					
k) Abandon the place only after trying to fight the fire					
l) Look for other persons (family / friends)					
m) Close the doors behind you when leaving the building					
n) Panicked					
o) Stay calm					
p) Other; which					

Please note: Select the options indicating the order of priority 1,2,3,.. (0=option not selected)

Expert Panel evaluation chart:

2nd SCENARIO– variant 2 **Fire alarm reaction – questionnaire in which there are multiple sites (home, school ,office, cinema, shopping)**	**Variant 1 or 2** **Please select one**	**If you do not agree or have other suggestions please write your comments here**
Which scenario do you think is best, having just one based location or different possible locations (home, school, office, cinema, shopping), variant 1 or 2?		

<u>Please note</u>: scale 1-5 (1-totally disagree; 2-disagree; 3-neither agree nor disagree; 4-agree; 5-totally agree)

B) Videogame: Subject is watching a movie (for 2 or 3 minutes) and then the fire alarm sounds...

Before the game starts, the player is informed that they should press the key "I" when listen the fire alarm. The game will play different alarms (Scenario 2 will be used here).

When the subject presses the "I" key, the following question is shown:

a) Keep on doing the same activity: __ (write priority option; 0=option not selected)
b) Call someone (close family, friends): __
c) Try to warn neighbours /other family/colleagues, warning about the fire: __
d) Call the firemen: __
e) Call 112/911: __
f) Search the fire location: __
g) Try to fight the fire using the portable fire extinguisher: __
h) Try to fight the fire using fire blanket or a wet cloth: __
i) Try to fight the fire using water using a bucket: __
j) Abandon the place immediately without trying to fight the fire: __
k) Abandon the place only after trying to fight the fire: __
l) Look for other persons (family / friends): __
m) Close the doors behind you when leaving the building: __
n) Panicked: __
o) Stay calm: __
p) Other. Which?:____

Select the options indicating the order of priority 1,2,3,.. (0=option not selected)

Expert Panel evaluation chart:

2nd SCENARIO – VIDEOGAME Fire alarm reaction	Do you agree? (Y/N)	If you do not agree which alternatives to you propose?
Do you agree with this game scenario in which the questions should be answered after the subject pressing a key, acknowledging that they heard the fire alarm?		

3rd SCENARIO 3 – Choice of exit from the initial room

Goal: try to establish if there is a pattern of subjects when leaving a room to turn to the same side. Compare results with the subject's dominant hand and figure out if there is any connection.

A) Questionnaire:

Imagine you are inside a building in a certain location with two possible exits; suppose that both exits are valid and the distance to the outside is exactly the same; in the condition shown of Fig.1 which exit would you choose, left or right? (see Figure 1a e 1b)

a) Left
b) Right

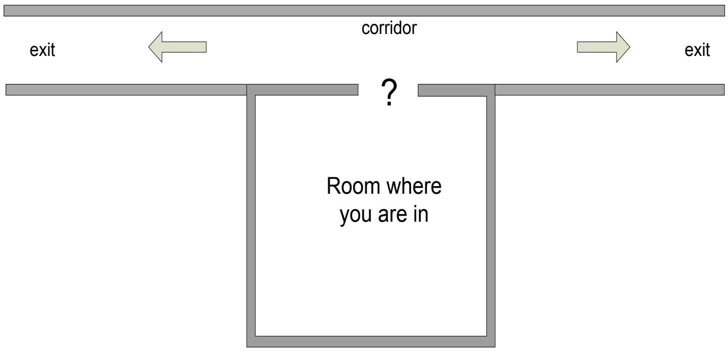


Figure 1a: Room with two possible exits

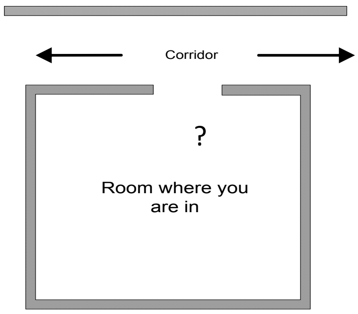


Figure 1b: Room with two possible exits

B) Videogame: subject is placed in a room; the fire alarm sounds. Player has to steer the game character towards one of the possible exits, when leaving the room, either left or right. Game saves the subject choice. Afterwards they will be compared, both the questionnaire answer and the game choice.

Repeat the scenario with 3 variants:

- **Variant 1:** use escape signage to show one exit as the shortest one (for example, left**)**
- **Variant 2:** use escape signage to show one exit as the shortest one (for example, left), but there is fire and smoke blocking it
- **Variant 3:** use escape signage to show one exit as the shortest one (for example, left), but there are some characters running from that direction towards the opposite one (the goal is to test if the subject follows the signage or the other characters)

Expert Panel evaluation chart:

3rd SCENARIO Room exit choice (right or left?)	Evaluation (scale 1-5)	If you do not agree or have other suggestions please rephrase the question (or write your comments here)
Imagine you are inside a building in a certain location with two possible exits; suppose that both exits are valid and the distance to the outside is exactly the same; in the condition shown of Fig.1 which exit do you will choose, left or right?		
Which is best, clearer to the question purpose Fig. 1a or fig1b?	**Select Fig.1a or Fig.1b**	

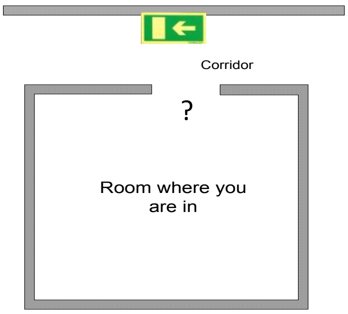
Please note: scale 1-5 (1-totally disagree; 2-disagree; 3-neither agree nor disagree; 4-agree; 5-totally agree)

Variant 1: escape signage showing one direction (for instance: left)

A) Questionnaire:

Suppose you are at the same location, but now there is escape signage as shown in Fig.2; when leaving the room after hearing the fire alarm, which direction do you choose?

a) Left
b) Right



B) Videogame: same scenario with escape signage showing the direction; fire alarm sounds and player has to steer the game character towards the exit; games saves the subject choice.

Expert Panel evaluation chart:

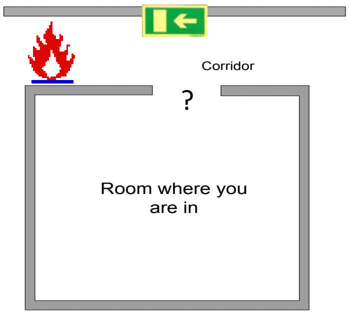
3rd SCENARIO – variant 1 Exit choice (left or right?) now with escape signage	Evaluation (scale 1-5)	If you do not agree or have other suggestions please rephrase the question (or write your comments here)
Same scenario now having escape signage pointing the direction to the best exit		

Please note: scale 1-5 (1-totally disagree; 2-disagree; 3-neither agree nor disagree; 4-agree; 5-totally agree)

Variant 2: escape signage showing one direction (for instance: left) but the corridor in that direction is blocked with fire and smoke

A) Questionnaire:

1. Same scenario as before, with the escape signage showing one direction but the corridor in that direction is blocked with fire and smoke, as shown in the figure; which direction would you choose?
   a) Left
   b) Right



B) Videogame: same scenario with escape signage showing the direction; fire alarm sounds and player has to steer the game character towards the exit; but this time, the corridor in that direction is filled with smoke, flames can be seen and fire sounds are heard. Player has to steer the game character towards the exit; game saves the subject choice.

Expert Panel evaluation chart:

3rd SCENARIO – variant 2 **Exit choice (left or right?) now with escape signage, but corridor is blocked with fire and smoke**	**Evaluation** **(scale 1-5)**	**If you do not agree or have other suggestions please rephrase the question (or write your comments here)**
Same scenario now having escape signage pointing the direction to the best exit; but with the corridor in that direction blocked with fire and smoke		

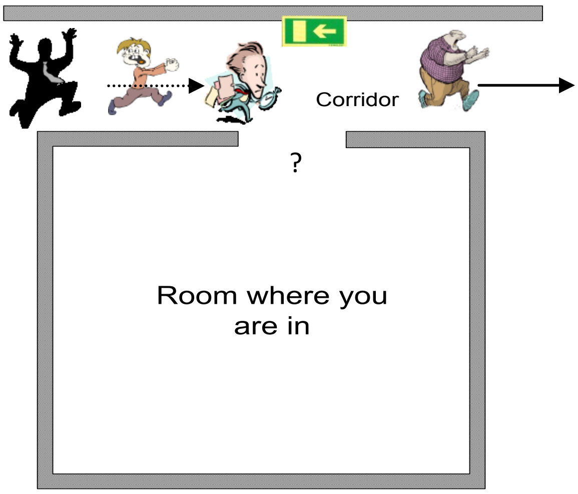
Please note: scale 1-5 (1-totally disagree; 2-disagree; 3-neither agree nor disagree; 4-agree; 5-totally agree)

Variant 3: signage shows one exit as the shortest one (for example, left), but there are some characters running from that direction towards the opposite one.

A) Questionnaire:

Same scenario as before, with the escape signage showing one direction but when leaving the room you face people running on the opposite direction of the escape signage; which direction would you choose?

a) Left
b) Right



B) Videogame: Same scenario as before, with the escape signage showing one direction but when leaving the room some characters appear running on the opposite direction of the escape signage. Player has to steer the game character towards the exit; game saves the subject choice.

Expert Panel evaluation chart:

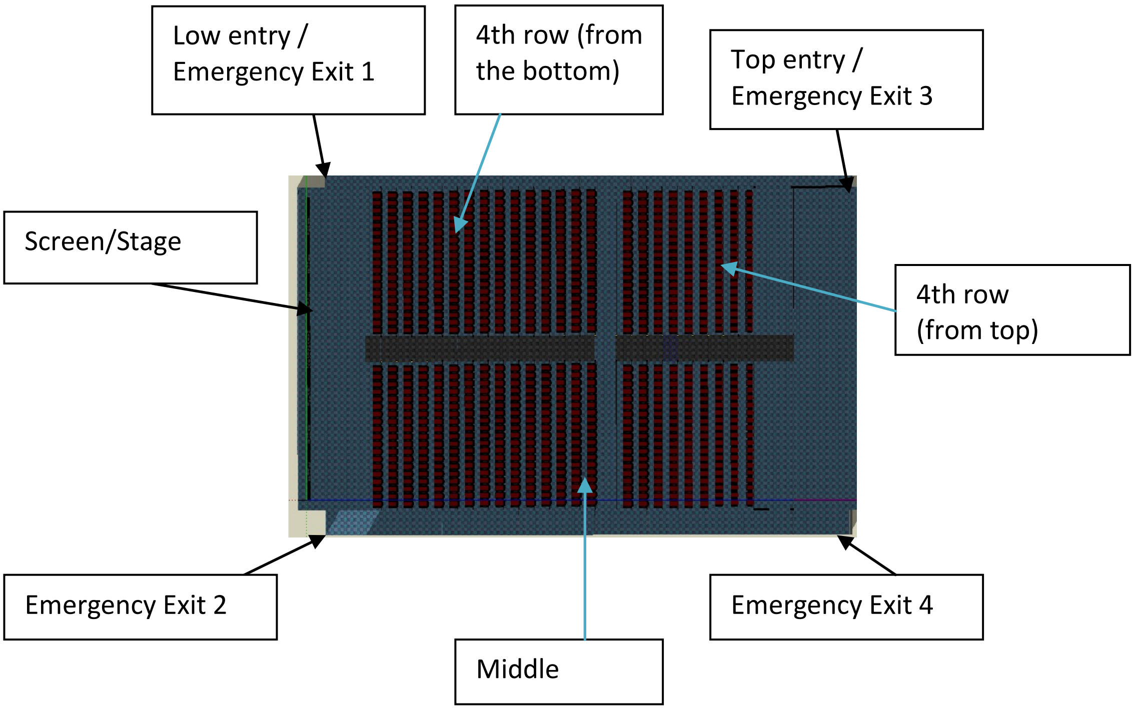
3rd SCENARIO – variant 2 **Exit choice (left or right?) now with escape signage, but there are some characters running from that direction towards the opposite one**	**Evaluation** **(scale 1-5)**	**If you do not agree or have other suggestions please rephrase the question (or write your comments here)**
Same scenario as previous, having the escape signage showing one direction but when leaving the room you face people running on the opposite direction of the escape signage.		

Please note: scale 1-5 (1-totally disagree; 2-disagree; 3-neither agree nor disagree; 4-agree; 5-totally agree)

4th Scenario– Auditorium

Goal: Assess if human behaviour is compliant with Portuguese fire codes which establish that occupants shall egress evenly using both up and down exits when the auditorium has a certain inclination and more than 12 rows (*n.º 3 do Artigo 55.º da Portaria 1532/2008*).

The subject is in three possible locations in the auditorium: up (far from the screen/stage), middle, down (near the screen/stage). The normal access might be either using up or down entries. The experiment goal is to find out which is the exit choice for each of these possibilities.



A) Questionnaire:

If you were in one of the following situations, which exit would you choose?

1. **You accessed the auditorium using the top access (top entry / emergency exit 3) and sat in the 4th row (counting from the top); if the fire alarm sounds, which exit will you choose?**
   a) The one you used to access the auditorium;
   b) The Emergency Exit below (emergency exit 1);
   c) I don't know
   d) Other. Which? :_________

2. **You accessed the auditorium using the top access (top entry / emergency exit 3) and sat in the middle of the room; if the fire alarm sounds, which exit will you choose?**
   a) The one you used to access the auditorium;
   b) The Emergency Exit below (emergency exit 2);
   c) I don't know
   d) Other. Which? :_________

3. **You accessed the auditorium using the top access (top entry / emergency exit 3) and sat in the 4th row (counting from the bottom); if the fire alarm sounds, which exit will you choose?**
   a) The one you used to access the auditorium;
   b) The Emergency Exit below (emergency exit 2);
   c) I don't know
   d) Other. Which? :_________

4. **You accessed the auditorium using the low entry (low entry / emergency exit 1) and sat in the 4th row (counting from the top); if the fire alarm sounds, which exit will you choose?**
   a) The one you used to access the auditorium;
   b) The top entry / Emergency Exit up (emergency exit 3);
   c) I don't know
   d) Other. Which? :_________

5. **You accessed the auditorium using the low entry (low entry / emergency exit 1) and sat in the middle of the room; if the fire alarm sounds, which exit will you choose?**
   a) The one you used to access the auditorium;
   b) The top entry / Emergency Exit up (emergency exit 3);
   c) I don't know
   d) Other. Which? :_________

6. **You accessed the auditorium using the low entry (low entry / emergency exit 1) and sat in the 4th row (counting from the bottom); if the fire alarm sounds, which exit will you choose?**
   a) The one you used to access the auditorium;
   b) The top entry / Emergency Exit up (emergency exit 3);
   c) I don't know
   d) Other. Which? :_________

Expert Panel evaluation chart:

4th SCENARIO– Auditoriums **Questionnaire**	**Evaluation** **(scale 1-5)**	**If you do not agree or have other suggestions please rephrase the question (or write your comments here)**
Questions: 1 to 6 (various combinations), do you agree with these questions?		
Do you agree with the possible answers to choose from?		
Scenario image: do you think that the image is clear enough for the subject?		
Do you think it would be better to provide 3D images of the Auditorium and the various situations to better understanding?		

Please note: scale 1-5 (1-totally disagree; 2-disagree; 3-neither agree nor disagree; 4-agree; 5-totally agree)

B) Videogame: 3D scenario in which the subject goes to an auditorium having at least 12 seat rows. Character gets inside the auditorium from the top entry and seats in the top/middle/lower section (several runs). After a while, the fire alarm sounds and the player has to steer his/her avatar towards the exit (choose which one). Later, the experimenter will compare the selected choice with the answers given to the questionnaire.

Expert Panel evaluation chart:

4th SCENARIO 4 – Auditoriums **Videogame**	**Evaluation** **(scale 1-5)**	**If you do not agree or have other suggestions please rephrase the question (or write your comments here)**
Do you agree with the scenario expected for the videogame?		
Do you think that it is important to repeat the videogame in the auditorium scenario with variant 1, in which the door used to access the auditorium is blocked with fire?		
Do you think that it is important to repeat the videogame in the auditorium scenario with variant 2, in which the nearest emergency exit is blocked with fire?		
Do you think that it is important to repeat the videogame in the auditorium scenario with variant 3, in which people inside the auditorium are running from the nearest emergency exit, to the opposite direction?		
Do you want to propose other possibilities? If yes, please describe them	*****	

<u>Please note</u>: scale 1-5 (1-totally disagree; 2-disagree; 3-neither agree nor disagree; 4-agree; 5-totally agree)

Appendix B

Expert panel short biography (in alphabetic order).

António Leitão – Civil Engineer and Master in Fire Safety for Urban Buildings from the University of Coimbra. Currently Board Director of PROJAR SGPS SA, a holding group specialised in passive fire safety equipment. Previously was General Manager of SISAF, a Portuguese fire proof doors manufacturer and Fire Safety Engineer at Consulfogo.

António Mota – Fire chief of the Porto Fireman Battalion, "BSB Porto", for more than 35 years. Holds a specialization course in Fire Safety for buildings inspections. Has considerable experience in fire fighting, as well as search and rescue operations in urban fires. Has lead many inspections and audits to buildings within the Municipality of Porto.

Carlos Losada Ferreira – Electrical Engineer (FEUP), Master in Fire Safety for Urban Buildings (University of Coimbra). Presently is a Senior Project Manager at Sonae Capital. Expert in Building Management including: Project design, Consulting, Commercial and Technical Management and Multi-Team Leadership. Prior to this, was a founder and general manager at Realseg, Regional Director at Prosegur, North Branch Manager at Siemens Buildings Technologies, Branch Manager and member of the Board of Directors at "Cerberus, Engenharia de Segurança" and Marketing Manager at "Microprocessador". Specialized in Electrical and Mechanical Infrastructures, Building Management Systems, Security and Safety Systems and Energy Management.

Elisabete Cordeiro – Electrical Engineer and Master in Fire Safety for Urban Buildings from the Coimbra University. Currently reading for a PhD at University of Coimbra, Fire Safety Engineering Doctoral Program. Founder and owner of "ENGSEGINC – Engenharia de Segurança aos Incêndios, Unipessoal Lda", where has authored many fire permit projects as well as emergency plans. Her specialisation research is buildings' evacuation in fire situations.

Elisabetta Carratin – is a licensed professional Architect who holds a Ph.D. in Architectural Technologies from IUAV University of Venice. She has worked, since 2006, as a researcher and teaching assistant in the field of architectural technologies and materials, especially in the field of fire safety, accessibility and sustainability. In 2009, conducted research on way-finding and human behaviour in fire, at the National Research Council Canada, with the late Dr. Proulx. Her principal interest is the interaction of the built environment with the safe design and use of structures. To this date her research has been into way-finding in various settings and fires related to a variety of architectural materials, systems and design. A published expert and lecturer on way-finding criteria for built environments as well as human behaviour in emergencies, she focuses her research efforts particularly on way-finding specific to emergency egress in complex environments.

Enrico Ronchi – Currently an Associate Senior Lecturer in Evacuation Modelling at the Department of Fire Safety Engineering at Lund University (Sweden). Previously worked as a Guest Researcher at University of Wurzburg, Germany; the Fire Research Division of the National Institute of Standards and Technology (NIST) in Gaithersburg (MD); and the GIDAI Group at University of Cantabria (Spain). Holds a Ph.D. from the Department of Roads and Transportation at the Polytechnic University of Bari (Italy). Member of the editorial board of the journal Fire Technology published by Springer in conjunction with the National Fire Protection Association (NFPA). Member of www.evacmod.net team - the Evacuation Modelling Portal. Peer-reviewer for International journals such as: Safety Science, Information Sciences, Fire Safety Science, Fire Technology, Fire Safety Journal, Physica A: Statistical Mechanics and its Applications, Applied Mathematical Modelling, Building Simulation. Specialized in: Evacuation Modelling, Human

Behaviour in Fire, Evacuation models validation, Virtual Reality, High-rise building evacuation, Elevator evacuation. Expert user of the following Evacuation models and fire risk analysis tools: FDS+Evac, STEPS, Pathfinder, NOMAD, MASSEgress, Simulex, GridFlow, CrowdControl, EXIT89, SFPE capacity method, FDS, Pyrosim. Regular user of Unity3d, SketchUp for Virtual Reality and 3D modelling.

Francisco Granadeiro – Mechanical Engineer, Post-graduation in Fire Safety (University of Coimbra), member of the Portuguese Professional Engineers Association (Azores Branch), and certified designer by *Autoridade Nacional de Protecção Civil* (ANPC). Specialised in fire permits, emergency plans, fire risk analysis, fire risk audits, validation of technical project designs, project management and supervision in the fields of smoke control, sprinklers, fire prevention systems, fire extinguishing systems, fire detection, passive protection systems. Frequent user of performance based design (PDB) using computer modelling software including CFAST and FDS. Formely managing partner of *H. Vaultier (Açores), Comércio de Máquinas e Ferramentas, Lda* for 30 years.

Irene Mealha - Chemical Engineer (*Instituto Superior Técnico*), holds a Master in Fire Safety for Urban Buildings (Coimbra University). Currently leading the Fire Safety division of Azores Civil Protecion and Fire Safety, where she has been promoting the application of fire codes in the region for the last 16 years, integrating several working committees on fire safety, as well as participating in and delivering workshops, lectures and conferences. Following her Masters' thesis, titled "Safety measures against fires in World heritage Angra do Heroismo". She has authored five papers on the subject, one of which was published in the journal "*Segurança*".

Joaquim Filipe Caldas – Electrical Engineer, Fire fighter since 2002, telecomunications operator at *Autoridade Nacional de Protecção Civil* (ANPC) between 2006 e 2013 (forest fires). Holds specialization courses in: life safety; first aids; vehicle extraction and victim stabilisation, emergency vehicle crew, by the Fire Fighters National School. Large experience in team leading in fires, traffic accidents and pre-hospital emergency.

José Manuel Silva – Senior Civil Engineer (Militar Academy), holds a Master in Fire Safety for Urban Buildings (Minho University). Holds a Post-graduation in Human Engineering (Health and Safety at Work) from TÜV Rheinland, Lisbon, Portugal. Currently is the Deputy Commander of the City of Porto Fire Brigade. Previously was the head of the Technical Department in charge of issuing the Fire Permits for the city Council.

Maria da Luz Santiago – Electrical Engineer (FEUP), holds a Master in Fire Safety for Urban Buildings (Coimbra University). Author of many fire permit projects for complex buildings such as commercial centres, secondary and high schools, universities, large industries, hospitals. Currently is a Senior Engineer and project manager at "*Afaconsult*". Has several post-graduations in the area of Fire Safety Engineering and a Master Degree in Fire Safety for Urban Fires. Nowadays, is in charge of the Safety and Security area at "*Afaconsult*".

Michael Kinsey – Holds a BSc (Hons) in Computer Science and a PhD in Computing and Mathematical Science, both from the University of Greenwich, London, UK, where worked under supervision of Professor Galea within the Exodus project. Presently is a Fire Engineer within Arup where is a specialist in human behaviour in fire and evacuation modelling. Has published a number of conference and journal papers. He is also a reviewer for a number of scientific journals within the field. Before was a Postdoctoral Research Fellow (University of Greenwich) having main focus of research involved with developing the buildingEXODUS and human behaviour models (in C++). He was also involved in the EU funded GETAWAY Project and the GEAD Project conducting an evacuation analysis of an offshore Oil Rig. Prior was Lloyds Register Research Assistant

(University of Greenwich) working with Exodus Maritime Evacuation modelling: HMS Victory (Royal Navy) CVF (Future Aircraft Carrier, Royal Navy).

Miguel Gonçalves – Civil Engineer, holds a Master and PhD in Civil Engineering. Presently is Assistant Professor at Faculty of Engineering of University of Porto (FEUP). Chair in the subject of Fire Safety at the Civil Engineering Department at FEUP. Has supervised a number of Master thesis and PhD thesis in the subject of Fire Safety.

Paulo Figueiredo – Civil Engineer and Master in Fire Safety for Urban Buildings (both at FCTUC Coimbra University). Post graduate degree in Health and Safety and Work. Certified trainer, lecturing in seminars and post-graduate courses. District and supra-regional coordinator (north-centre region) at ANPC (Portuguese Civil Protection and Fire Safety Agency).

Paulo Prata Ramos – Architect since 1996, holds a Master in Architecture, Postgraduate in Fire Safety for Urban Buildings (Coimbra University). Indicated by the Portuguese Architects Association to the Monitoring Committee representative for the Fire Safety Legislation. University lecturer, trainer at many courses in Fire Protection Design, frequently invited for congresses as speaker. Owner and managing partner of ETU architects office. Technical Director at Culturgest. Previously was Technical Director at Teatro São Luiz and Teatro Camões.

Regina Ferreira – Civil Engineer (FEUP), Postgraduate in Real Estate Management (FEP). Holds a specialization course in Fire Safety for buildings. Has a long career at Porto Municipality, first at the work supervision and inspections department, and in the past years as head of the Technical Department in charge of issuing the Fire Permits for the city Council at the Porto Fireman Battalion.

Rodrigo Machado Tavares – holds a PhD in Fire Safety from the Greenwich University, UK. Currently is the CEO of RMT Engineering, a consultancy company specialized in Fire Safety Engineering and related areas, such as Crowd Modelling, Fire Modelling. Experienced in the Design Projects and Installation of Passive Fire Protection and Active Fire Protection systems involving the early stages (Request For Proposal and Request For Quotation) as well as the Project Management. Has over 14 years of experience working with clients from around the globe. Worked for some years at ARUP Fire, London, UK.

Rui Figueira – Civil Engineer, holds a Masters in Fire Safety for Urban Buildings (Coimbra University), Director of the Civil Protection Office of the Funchal Municipality, Madeira. Previously was deputy at the Funchal Fireman Brigade.

Sílvio Saldanha – Holds a degree in Marketing. Has been working in the fire passive protection market for over 20 years. Specialized salesman on equipment such as fire-resistant materials (doors, glass), fire barriers, ducts protection, fire-retardants. Manager of the company for some years now, has a long experience in the fire safety area. Made part of the organizing committee of many seminars and courses on fire safety in Portugal.

Vítor Primo – Civil Engineer (Militar Academy), holds a Masters in Fire Safety for Urban Buildings (Coimbra University). Portuguese Army Major, was the Commander of the Porto Fireman Battalion, previously second Commander, before being in charge of the technical committee issuing buildings' fire permits for Porto. For some time, was responsible for the larger metropolitan Porto area (ANPC CDOS/Porto). Currently is a university lecturer at Lusófona University of Porto.

Appendix C

Tables with the results from the expert panel questionnaire, aggregated by sections.

Section I - Subject characterization

Section I - subject characterization (*)	1	2	3	4	5
Age	0	0	0	1	15
Gender	0	0	0	0	16
Dominant Hand	0	0	2	0	14
Education	0	0	0	0	16
Profession	0	0	0	1	15
Computer expertise	0	0	2	3	11
Games expertise	0	0	2	3	11

(*) 1-Strongly Disagree; 2-Disagree; 3-Neither Agree Nor Disagree; 4-Agree; 5-Strongly Agree

Section II – Knowledge on fire safety

Section II – knowledge on fire safety (*)	1	2	3	4	5
Fire Training (FT)	0	2	0	2	12
FT areas	0	4	0	2	10
FT periodicity	0	1	1	4	10
Fire-Related Experience	0	1	2	3	10
Where?	0	1	1	4	10
What?	0	1	2	3	10
Behaviour	0	1	0	6	9
Activity Influence	0	2	2	2	10

(*) 1-Strongly Disagree; 2-Disagree; 3-Neither Agree Nor Disagree; 4-Agree; 5-Strongly Agree

Section IV: Experiment 1 Fire Alarm Id

Experiment 1: Fire Alarm Id (*)	1	2	3	4	5
Fire Alarm Id	0	1	2	2	11
Fire Alarm Sounds	0	1	1	2	12
a) fire alarm	0	0	1	3	12
b) theft alarm	0	0	1	3	12
c) siren of emergency vehicle	1	2	1	5	7
d) fire truck	1	2	2	6	5
Game	0	0	1	7	8
a) multiple choice	2	0	4	1	9
b) write answer	5	4	2	1	4

(*) 1-Strongly Disagree; 2-Disagree; 3-Neither Agree Nor Disagree; 4-Agree; 5-Strongly Agree

Section IV: Experiment 2 Alarm reaction

Experiment 2: Alarm reaction (*)	**1**	**2**	**3**	**4**	**5**
Question: Imagine that you are at home (watching TV or cooking, for instance), in the movies, or at a class and suddenly the fire alarm sounds, what do you do?	2	2	3	2	7
a) Keep on doing the same activity	0	2	3	1	10
b) Call someone (closed family, friends)	0	1	4	2	9
c) Try to warn neighbours /other family/colleagues, warning about the fire	2	1	3	2	8
d) Call the firemen (direct number)	0	1	3	2	10
e) Call emergency number (112/911)	0	1	3	2	10
f) Search the fire location	0	0	4	2	10
g) Try to fight the fire using the portable fire extinguisher	1	0	3	1	11
h) Try to fight the fire using fire blanket or a wet cloth	0	2	3	2	9
i) Try to fight the fire using water using a bucket	0	0	3	3	10
j) Abandon the place immediately without trying to fight the fire	0	0	3	1	12
k) Abandon the place only after trying to fight the fire	0	0	3	1	12
l) Look for other persons (family / friends)	0	2	3	1	10
m) Close the doors behind you when leaving the building	0	2	3	1	10
n) Panicked	1	0	5	1	9
o) Stay calm	0	1	5	0	10
p) Other. Please describe	1	0	5	1	9

(*) 1-Strongly Disagree; 2-Disagree; 3-Neither Agree Nor Disagree; 4-Agree; 5-Strongly Agree

Section IV: Experiment 3 Exit Choice

Section IV; Scenario 3 Exit Choice (*)	**1**	**2**	**3**	**4**	**5**
questionnaire scene 1	0	2	2	5	7
" " scene 2	0	2	0	2	12
" " scene 3	0	1	1	5	9
" " scene 4	0	1	2	3	10

(*) 1-Strongly Disagree; 2-Disagree; 3-Neither Agree Nor Disagree; 4-Agree; 5-Strongly Agree

Section IV: Scenario 4 - Auditorium

Section IV: Scenario 4 – Auditorium (*)	1	2	3	4	5
Questions 1 to 6, do you agree with the questionnaire?	0	1	1	4	10
Questions: 1 to 6 (various combinations), do you agree with these questions?	0	1	0	4	11
Scenario image: do you think that the image is clear enough for the subject?	1	5	0	4	6
Do you think it would be better to provide 3D images of the Auditorium and the various situations to better understanding?	4	0	0	6	6
Do you agree with the scenario expected for the videogame?	0	0	1	2	13
Do you think that it is important to repeat the videogame in the auditorium scenario with variant 1, in which the door used to access the auditorium is blocked with fire?	0	0	0	6	10
Do you think that it is important to repeat the videogame in the auditorium scenario with variant 2, in which the nearest emergency exit is blocked with fire?	0	0	0	7	9
Do you think that it is important to repeat the videogame in the auditorium scenario with variant 3, in which people inside the auditorium are running from the nearest emergency exit, to the opposite direction?	1	0	0	5	10

(*) 1-Strongly Disagree; 2-Disagree; 3-Neither Agree Nor Disagree; 4-Agree; 5-Strongly Agree

Appendix D

This appendix presents further information and results concerning the experiments made using UWB for pedestrians' trajectory extraction, described earlier on Section 3.6.2. The research made had as outcome a paper presented at the 24th European Modelling & Simulation Symposium – EMSS 2012 (Vasconcelos et al., 2012) and a Master thesis (Vasconcelos, 2013).

The experiments were performed in classroom B227 in the Faculty of Engineering of the University of Porto. The area in which the experiments took place was confined within a section of 7m x 15m of the room, where the only metallic elements present were from the tables that made up barriers for delimiting the track for the experiments (see Figure D.1).

Figure D.1: Some photographs of participants during the experiments.

After being secured at a height of 2.3 m from the ground, four sensors were placed in the four vertices of the bounding rectangle containing the area where experiments took place. Within this area, different scenarios were built using tables and a vinyl foldable wall. Tag placement plays an important role in ensuring that good readings will be achievable. Tags become difficult to read when they are in close proximity to materials that absorb a large amount of radio frequency energy, such as water, that makes up most of the human body. For the purposes of these experiments, tags were attached on top of Christmas hats secured with straps (see Figure D.1 right and D.2 left).

The UWB system used for data collection asynchronously reads tags' location. Consequently the location of the crowd is updated one pedestrian at a time. Moreover, the system does not ensure a constant frequency of readings for each tag. The mean frequency of location updates for a single tag in the collected data was 4.74 ± 1.74 Hz. This compares unfavourably with other collection techniques, such as video where frequencies of 25 Hz are common and each frame contains data about all pedestrians.

Figure D.3: Experiment setup – Christmas hats with tags; Room layout made with tables and chairs; Antenna with sensor.

During the experiments, the application developed to interface with the Ubisense API gathered the location events of the tag in the measurement area and recorded the information in text files. A different file was created for each experiment. Then, a visualization tool developed using Unity3D for the project takes the log files as input and provides a graphical representation of the tags positions and movement over time in a three-dimensional environment. Figure D.3 shows the tool in use with data from the one of the experiments.

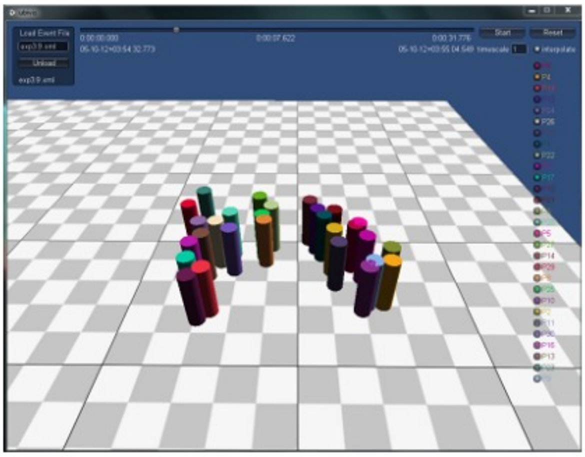


Figure D.3: Screenshots of the visualization tool developed using Unity3D.

The application can playback the experiments at different time-scales and allows choosing which tags are shown or hidden. Although this tool presents limited use for analysis, it provided an early insight into the collected data and allowed to understand some limitations of the tracking system. It also allowed the realization that one of the tags used during the experiments - ’P11’ - behaved erratically, and therefore the data associated with that specific tag should be discarded. Another usage was to define the precise instants of the start and end of each experiment.

Trajectories were constructed for each pedestrian, whose representation for some experiments is presented in Figure D.4a. The collected trajectories appear to be jerky and imprecise. Considerable noise seems to affect some measurements as some trajectories are drawn outside the physically delimited track bounds, where pedestrians would be unable to reach. The inaccuracies of the positioning system explain the irregularities in the trajectories, and can be attributed to imprecision in the calibration process, limitations of the information filter used by the location system framework, background noise, the agglomeration of large number of tags in confined areas and the signal attenuation caused by the presence of a large number of test persons.

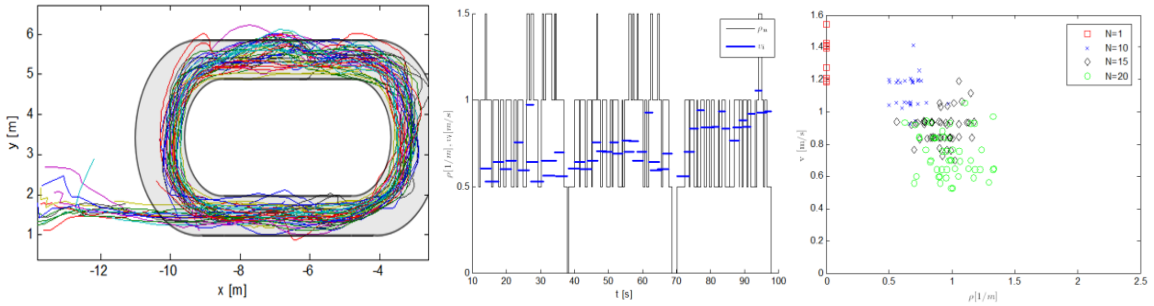


Figure D.4: a) Extracted trajectories for the single-file scenario b) Evolution of speed vi and density ρn over the duration of the experiment composed of 20 participants. Tick blue lines, whose length indicates the time interval a pedestrian is inside the measurement section, represent the mean velocity of the crossing. c) Relation between density and velocity in the single file scenario for the runs with 1, 10, 15 and 20 participants.

For the singe-file scenario only a straight section with length l_m = 2 m was considered to determine the density-velocity relation of pedestrian movement (see Figure 3.10c in Section 3.6.2). Entrance (t^{en}) and exit (t^{ex}) times were recorded for each pedestrian crossing the entrance (x^{en}) and exit (x^{ex}) of this section. From these times, both the average velocity (see eq. D.1):

$$v_i = \frac{l_m}{t_i^{ex} - t_i^{en}} \tag{D.1}$$

of each crossing *i* as well as the number of persons inside the measurement section *N(t)* at each instant *t* can be obtained. Taking into consideration the large period between consecutive measurements for each tag, a linear interpolation between the positions and instants when each tag is first located inside (x_i^{in}, t_i^{in}) or outside (x_i^{out}, t_i^{out}) the measurement section and the positions and times associated with the previous locations (x_i^{in-1}, t_i^{in-1}, x_i^{out-1}, t_i^{out-1}) are necessary to better estimate the exact entrance and exit times:

$$t_i^{en} = t_i^{in-1} + \left[\left(t_i^{in} - t_i^{in-1} \right) \frac{x^{en} - x_i^{in-1}}{x_i^{in} - x_i^{in-1}} \right] \tag{D.2}$$

$$t_i^{ex} = t_i^{out-1} + \left[\left(t_i^{out} - t_i^{out-1}\right) \frac{x^{ex} - x_i^{out-1}}{x_i^{out} - x_i^{out-1}}\right] \qquad (D.3)$$

From the runs with a single pedestrian on the track, the free velocity v_{free} = 1.33 ± 0.13 m/s, was obtained, which matches well with the value from literature (1.34m/s) (Kady et al., 2009).

Density at each instant *t* can be obtained from the instantaneous number of pedestrians *N* inside the measurement section.

$$\rho(t) = N(t)/l_m \qquad (D.4)$$

As the measurement section is short, only small numbers of persons can be inside. Consequently the value of density calculated from the above definition jumps between discrete values. An enhanced definition of the density, calculated through the time headways between successive pedestrians avoids this problem, but its calculation is a challenging task as the data collection system is unable to provide the location of two tags at the same instant, and also because inaccuracies would increase as error from two different measurements would have to be taken into account.

The density assigned to each pedestrian crossing the measurement section is determined as the mean value of density during the crossing (eq. D.5):

$$\rho_i = \frac{1}{t_i^{ex} - t_i^{en}} \int_{t_i^{en}}^{t_i^{ex}} \rho_n dt \qquad (D.5)$$

The differences between the mean value of density over time determined by this method or by the time headway method is negligible (Chattaraj et al., 2009). Figure D.4b shows the evolution of the crossings' speed and density in the measurement section over the whole duration of the run with 20 pedestrians. A graphical representation of the velocity (v_i) - density (ρ_i) pairs of each crossing is presented in Figure D.4c. This representation is known as the fundamental diagram of pedestrian movement.

In comparison with the diagrams obtained from similar experiments (Chattaraj et al., 2009; Schadschneider et al., 2009; Tian et al., 2012), where data was collected manually from video recordings, similar values for density and velocity are found for runs with the same number of participants. However, the experiment diagram is more disperse as a result of the limited precision of the UWB system.

In order to assign densities at different temporal instants to the different zones of the experiment area, a Voronoi partition of space, where the position of the tags is input as seeds to the method, is performed. For each instant t, the cells obtained by the method represent the personal area occupied by each pedestrian at that instant. This allows measuring the density in any point in space as the reciprocal of the area of the cell that the point belongs to. Figure 4.20 represents the partition of space in different experiment areas according to the Voronoi method at a certain instant. The crosses represent the position of pedestrians and the labels show the density to assigned to each.

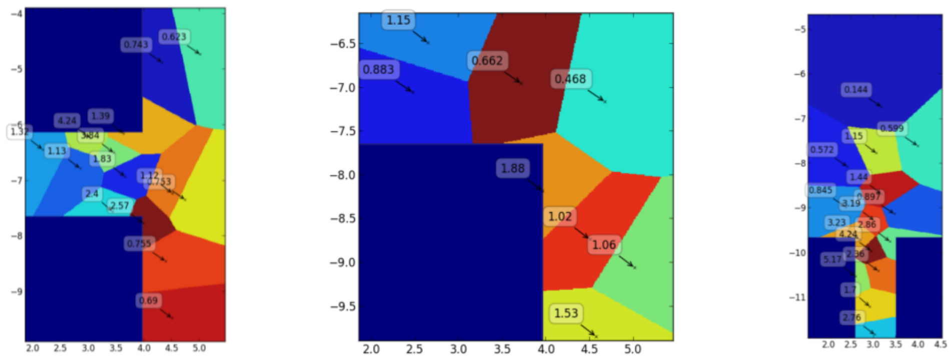


Figure D.5: Partition of space according to the Voronoi method for the T-junction, corner and bottleneck experiments.

This project has accomplished to achieve several goals: to study and improve techniques of tracking human movement using UWB RFID tags; to conduct experiments with volunteers and record tracked trajectories; to extract relevant information from the recorded trajectories. Several experiments of pedestrian movement in restricted areas were devised and conducted, from which trajectories were recorded by a UWB RDIF tracking system. From the results analysis it can be conclude that the Ubisense RTLS lacks the fine spatial precision that would be desired to make extensive quantitative analysis of motion at the scales relevant for characteristics of movement such as velocities and accelerations. It can be also reason that although the system has a complex and time-consuming setup and installation, its usage and handle is relatively accessible. Usage of this technology presents several advantages over traditional data collection techniques, expanding the breath of possible scenarios for experiments, such as situations of limited visibility for which data is inexistent. Compared with the usual method for tracking of people trajectories, video recordings, UWB allows use in narrower spaces, facilities with lower ceilings and areas with line of sight restrictions. Other aspect is related with data collection. UWB based systems record the coordinates of position for each tag directly whereas video recordings must be later analysed and processed in order to extract positions / trajectories. Each tag carried by pedestrians is uniquely identifiable, allowing individual tracking and thus enabling the investigation of the behaviour and effect of specific individuals like child, elderly or people with mobility impairments on the crowd dynamics. UWB techniques for human trajectory extraction seems a viable approach. It is particularly suitable for scenarios where video is less applicable and pedestrian fine positioning is not an issue, such as for macroscopic analysis (e.g. egress time, path choice and behaviour scrutiny).

Concerning the information extracted from the trajectories, some limitations were found, like the lack of fine spatial precision. Attempts to improve the quality of the data by filtering and smoothing proved to be challenging tasks in this project. When it comes to extract relevant information from the recorded trajectories, it is also important to mention that adequate choice of parameters is fundamental to properly characterize and describe the motion behaviour patent in the trajectory data. The computed descriptors of movement, combined with the exploration of several different visualization techniques, provided insight into some of the processes of crowd congestion and emergency egress. The results from this step capture and describe the spatio-temporal behaviour of crowds, an important feature of evacuation dynamics. Such results can be used for improving facility design as well evacuation route planning.

Although the present study makes a contribution to pedestrian movement knowledge, it also intends to incite further research on the matter of the usage of UWB based tracking systems. This is a promising technology that widens the range of possible test scenarios for which there is scarce data such as low visibility situations, so common during evacuations due to fire or during the night. As this is a relatively new topic, there are still some subjects that remain unexplored, thus this promotes an opportunity for further investigation.

Appendix E

This appendix contains an exhaustive list of publications, conferences attended with presented and published papers, software applications developed and media exposure of the research done during the time that the present dissertation occurred.

Book Chapter

Almeida, João Emílio, Rossetti, Rosaldo J. F., Faria, Brígida Mónica, & Coelho, António Leça (2015). ***"Using Serious Games to Train Children and Elicit Fire Safety Behaviour"***. In Á. Rocha, A. M. Correia, S. Costanzo, & L. P. Reis (Eds.), New Contributions in Information Systems and Technologies (Vol. 353, pp. 1153–1162). Springer International Publishing. ISBN: 978-3-319-16485-4. doi:10.1007/978-3-319-16486-1_114

Almeida, João Emílio, Rosaldo J.F. Rossetti, Fábio Aguiar, and Eugénio Oliveira. 2014. ***"Crowd Simulation Applied to Emergency and Evacuation Scenarios."*** In Advances in Artificial Transportation Systems and Simulation, 149-161. ISBN-13: 978-0123970411 ISBN-10: 0123970415

Journals

João Emílio Almeida, Rosaldo J. F. Rossetti, Brígida Mónica Faria, António Leça Coelho (2015). ***Elderly and Fire Safety: using Serious Games to Elicit Human Behaviour in Evacuation Scenarios***. International Journal of the Digital Human, Special issue. Submited.

João Emílio Almeida, Rosaldo J. F. Rossetti, João Tiago Pinheiro Neto Jacob, Brígida Mónica Faria, António Leça Coelho (2014). ***Serious Games for the Elicitation of Way-finding Behaviours in Emergency Situations.*** Cluster computing. Submited and accepted.

Rosaldo J.F. Rossetti, Joao Emilio Almeida, Zafeiris Kokkinogenis, Joel Goncalves (2013). ***Playing Transportation Seriously: Applications of Serious Games to Artificial Transportation Systems.*** Intelligent Systems, IEEE. Volume:28 , Issue: 4, pp: 107 - 112.

Conference and Workshop papers

WorldCIST'15 - 3rd World Conference on Information Systems and Technologies, Ponta Delgada, São Miguel, Azores, Portugal
Almeida, João Emílio, Rossetti, Rosaldo J. F., Faria, Brígida Mónica, & Coelho, António Leça (2015). Using Serious Games to Train Children and Elicit Fire Safety Behaviour. doi:10.1007/978-3-319-16486-1_114

DSIE'15 - Doctoral Symposium in Informatics Engineering, Porto, Portugal

Oliveira, Marcos; Pereira, Nelson, Almeida, João Emílio; Rossetti, Rosaldo J.F.; Oliveira, Eugénio (2015) A Multi-player Approach in Serious Games: Testing Pedestrian Fire Evacuation Scenarios. In: DSIE'15 - Doctoral Symposium in Informatics Engineering, Porto, Portugal, pp 120-131, Jan 29-30, 2015. ***Best Paper Award***

EMSS 2014 - The 26th European Modeling and Simulation Symposium, Bordeaux, France
Almeida, João Emílio; Jacob, João Tiago P. Neto; Faria, Mónica Brígida; Rossetti, Rosaldo J.F.; Coelho, A. Leça (2014) Towards a Methodology for Human Behaviour Elicitation: Preliminary Results. In: EMSS - The 26th European Modeling and Simulation Symposium, Bordeaux, France, Sept 10-12, 2014.

Cultural Help 2014 - Cultural Heritage and Loss Prevention, Porto, Portugal
Almeida, João Emílio; Jacob, João Tiago P. Neto; Faria, Mónica Brígida; Rossetti, Rosaldo J.F.; Coelho, A. Leça (2014) The Importance of Prevention and Emergency Planning in Cultural Buildings. In: Cultural Heritage and Loss Prevention, 47-54, Porto, Portugal, Oct 6-7, 2014, edited by A. Arêde, E. Paupério, and X. Romão. DOI: 10.13140/2.1.1823.7763

CISTI 2014, Barcelona, Spain
Almeida, João Emílio; Jacob, João Tiago P. Neto; Faria, Mónica Brígida; Rossetti, Rosaldo J.F.; Coelho, A. Leça (2014) Serious games for the Elicitation of way-finding behaviours in emergency situations. In: CISTI'2014 (9th Iberian Conference on Information Systems and Technologies), Barcelona, Spain, Jun 18-21, 2014. DOI: 10.1109/CISTI.2014.6876951.

EMS 2013, Manchester, United Kingdom
Almeida, J.E.; Rossetti, R.; Coelho, L. (2013) Towards a Framework for Pedestrian Simulation for Intermodal Interfaces. In: 7th European Modelling Symposium (EMS2013), pp. 316-321, November 21st Manchester, United Kingdom, 2013.

ECMS 2013, Ålesund, Norway
Silva, J. F.; Almeida, J.E.; Pereira, A.M.; Rossetti, R.; Coelho, L. (2013) Preliminary Experiments with EVA - Serious Games Virtual Fire Drill Simulator. In: ECMS 2013 27th European Conference on Modelling and Simulation, May 27th - 30st, Ålesund, Norway, 2013.

WISA 2013, Lisbon, Portugal
Almeida, J.E.; Rossetti, R.; Coelho, A. L. (2013) Mapping 3D Character 3D Location for Tracking Players' BehaviourIn: WISA'2013 (Fifth Workshop on Intelligent Systems and Applications), Lisbon, Portugal, June 22, 2013.

SGaMePlay'2013, Lisbon, Portugal
Almeida, J.E.; Rossetti, R.; Coelho, A. L. (2013) Gamifying Evacuation Drills. In: SGaMePlay'2013 (Third Iberian Workshop on Serious Games and Meaningful Play), Lisbon, Portugal, June 22, 2013.

MECC 2013, Lisbon, Portugal
Coelho, A. L.; Almeida, J. E. (2013)Buildings' Fire Development and Evacuation Modelling.In: MECC 2013 - International Conference and Advanced School Planet Earth, Mathematics of Energy and Climate Change. March 25th, Lisbon, Portugal.

MECC 2013, Lisbon, Portugal
Almeida, J. E.; Rossetti, R. J. F.; Coelho, A. L. (2013)Modelling and Simulation of Pedestrian Emergency Evacuation DynamicsIn: MECC 2013 - International Conference and Advanced School

Planet Earth, Mathematics of Energy and Climate Change. March 25th, Lisbon, Portugal.

MECC 2013, Lisbon, Portugal
Kokkinogenis, Z.; Almeida, J. E.; Rossetti, R. J. F. (2013) NetLogo implementation for Crowd EvacuationIn: MECC 2013 - International Conference and Advanced School Planet Earth, Mathematics of Energy and Climate Change. March 25th, Lisbon, Portugal.

SeGAH 2013, Vilamoura, Portugal
Silva, J. F.; Almeida, J.E.; Rossetti, R.; Coelho, L. (2013) Using Serious Games to Train Evacuation Behaviour. In: SeGAH 2013 IEEE 2nd International Conference on Serious Games and Applications for Health, Vilamoura, Portugal, May 2-3, 2013.

WorldCIST'13, Algarve, Portugal
Ribeiro, J.; Almeida, J.; Rossetti, R.; Coelho, A.; Coelho, L. (2013) A collaborative tourist system using Serious Games. In: WorldCIST'13 (The 2013 World Conference on Information Systems and Technologies), Algarve, Portugal, March 27-30, 2013.

CISTI 2012, Madrid, Spain
Ribeiro, J.; Almeida, J.; Rossetti, R.; Coelho, A.; Coelho, L. (2012) Using Serious Games to Train Evacuation Behaviour. In: CISTI'2012 (7th Iberian Conference on Information Systems and Technologies), Madrid, Spain, Jun 20-23, 2012.

WISA 2012, Madrid, Spain
Almeida, J.E.; Kokkinogenis, Z.; Rossetti, R. (2012) NetLogo Implementation of an Evacuation Scenario. In: WISA'2012 (Fourth Workshop on Intelligent Systems and Applications), Madrid, Spain, June 20-23, 2012.

ECMS 2012, Koblenz, Germany
Ribeiro, J.; Almeida, J.; Rossetti, R.; Coelho, A.; Coelho, L. (2012) Towards a Serious Games Evacuation Simulator.In: 26th European Conference on Modelling and Simulation, Koblenz, Germany, May 29 - June 1, 2012.

EVAC 2011, Santander, Spain
Elisabete Cordeiro, António Leça Coelho, Rosaldo J F Rossetti, and João Emílio Almeida. 2011. Human Behavior under Fire Situations - A case-study in the Portuguese Society. In Advanced Research Workshop: Evacuation and Human Behavior in Emergency Situations, 63-80. Santander, Spain: GIDAI. Universidad de Cantabria.

FEMTC 2011, Baltimore, USA
Cordeiro, E.; Coelho, L.; Rossetti, R.; Almeida, J. (2011) Human Behavior Under Fire Situations - Portuguese Population. In Fire and Evacuation Modeling Technical Conference. Baltimore, Maryland, August 15-16,2011.

DSIE 2011, Porto, Portugal
Almeida, J. E., Rosseti, R., & Coelho, A. L. (2011) Crowd Simulation Modeling Applied to Emergency and Evacuation Simulations using Multi-Agent Systems. In A. A. Sousa & E. Oliveira (Eds.), DSIE'11 - 6th Doctoral Symposium on Informatics Engineering (pp. 93-104). Engineering Faculty of Porto University, Porto.

Software

ModP – Pedestrian Simulator (E.Esteves, F.Aguiar, J.E.Almeida, R.J.F. Rossetti, A.L.Coelho) Pedestrian Simulator using Multi-Agent Systems and BDI architecture.

ModP3D – Pedestrian Simulator 3D (J.P.Ribeiro, J.E.Almeida, R.J.F. Rossetti, A.L.Coelho) Pedestrian Simulator for training FEUP "I" building evacuations, based on the Serious Games concept and using the Unity 3D game engine.

EVA - Evacuation Simulator (J.F.Silva, J.E.Almeida, R.J.F. Rossetti, A.L.Coelho) Evacuation Simulator based on the Serious Games concept using the Unity 3D game engine, for training and elicitation of users' behaviours.

NetLogo Evacuation Simulator (J.E.Almeida, Zafeiris Kokkinogenis, R.J.F. Rossetti) Evacuation Simulator for discotheques or other rooms for events, based on the NetLogo Agent-Based Modelling and Simulation framework.

Media

Engenharia num minuto (RTP, Jornal Público, Rádio Nova)

Presentation (in Portuguese) of the short video at the "*Engenharia num minuto*" FEUP initiative, "RTP Informação", news TV channel (21 and 22 June 2012), "Jornal Público", national newspaper (23 June 2012) and "Rádio Nova" (21 June 2012), having the title: "*Jogo de Computador ajuda a desenvolver Planos de Emergência*".

Mentes que Brilham (in Portuguese) live interview in TV Channel, July 4, 2012

Live interview (in Portuguese) at the TV channel "Porto Canal", for the program "*Mentes que Brilham*", on July 4th 2012, reporter Cláudia Fonseca, about the ongoing research at FEUP and LIACC, within the PhD ProDEI, having focus on Serious Games, Artificial Intelligence, Agent-Based Simulation and Fire Safety.

