Universidade de Lisboa
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DEVELOPMENT OF A MODEL BASED ON VIRTUAL REALITY FOR THE EVALUATION OF BEHAVIORAL COMPLIANCE WITH WARNINGS AND WAYFINDING CONTEXTS

Dissertação elaborada com vista à obtenção do Grau de Doutor em Motricidade Humana,
na especialidade de Ergonomia

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Abstract

Virtual Reality (VR) when framed in adequate methodologies, has an ample field of application for Ergonomics and for Design, since it allows to analyze and understand how people interact with simulated situations in Virtual Environments (VEs). As such, it is of extreme importance for research and the practice of Ergonomics, to understand how it is possible to optimize, create, implement and evaluate solutions based in VEs in different contexts, including dangerous ones, in particular those that can place in risk the physical integrity of people. These VEs can be used to study Human Behavior in critical situations, which is important when projecting products and systems that involve dangers to the users that would be difficult to study otherwise.

In this context, this project has as its general objective the study of the factors that influence the development of VEs for VR and in the implementation of solutions (with a focus on software and hardware) that better can correspond to the development of this type of studies, namely in studies of behavioral compliance with warnings and in studies of wayfinding. The methodological proposal described in this document focuses in a User-Centered Design (UCD) perspective, which involved the participation of the users, in the different phases of development of the project. As a result, it were developed and evaluated software and hardware solutions for the understanding and evaluation of the factors associated to the study of Human behavior, namely in behavioral compliance with warnings and in wayfinding contexts.

It was also studied the best solutions for interaction and navigation in VEs, that correspond to high levels of presence, which is a fundamental aspect in behavioral compliance with warnings and wayfinding studies that use VR as a support tool. With this purpose, two navigational interfaces were developed (i.e., Balance Board and Walk-in-Place), also in a UCD perspective, to guarantee a constant cycle of tests and improvement of the implementations among the users. A comparative study was made between these two navigational interfaces and another that is commonly used in studies with VR (i.e., a Joystick). This comparative study was conducted in a context of evaluation of behavioral compliance with warnings and performance variables were analyzed, as well as the levels of presence in the different navigational interfaces. There were no statistically significant differences in the levels of presence or in the behavioral compliance between the three navigational interfaces. However, statistically significant differences were found in several performance variables (e.g., average speed, total distance). Future directions for the research are also discussed.

Resumo

A Realidade Virtual (RV) quando enquadrada em metodologias adequadas, tem um campo de aplicação alargado para a Ergonomia e o Design, visto permitir analisar e compreender como as pessoas interagem com situações simuladas em Ambientes Virtuais (AVs). Desta forma, é de extrema importância para a investigação ou prática da Ergonomia, perceber como se pode optimizar, construir, implementar e avaliar soluções baseadas em AVs em diferentes contextos, incluindo contextos perigosos, particularmente aqueles que podem colocar em risco a integridade física das pessoas. Estes AVs podem ser usados para estudar o comportamento Humano em situações críticas, o que é importante quando se projecta produtos e sistemas que envolvam perigos para os utilizadores que de outra forma seria muito difícil avaliar.

Neste contexto, este projecto tem como objectivo geral o estudo dos factores que influenciam o desenvolvimento de ambientes para Realidade Virtual e na implementação de soluções (com um foco maior no *software* e *hardware*) que melhor possam corresponder ao desenvolvimento deste tipo de estudos, nomeadamente em estudos de consonância comportamental com avisos de segurança e estudos de wayfinding. A proposta metodológica descrita neste documento foca-se numa perspectiva de Design Centrado no Utilizador (DCU), que envolveu a participação dos utilizadores, nas várias fases de desenvolvimento do projecto. Como resultado, desenvolveu-se e avaliou-se soluções de *software* e *hardware* para a compreensão e avaliação dos factores associados ao estudo do Comportamento Humano, nomeadamente para a consonância comportamental com avisos de segurança e para situações de wayfinding.

Foram também estudadas as melhores soluções para interacção e navegação em AVs, que correspondam a níveis de presença elevados, aspecto fundamental em estudos de consonância comportamental com avisos de segurança e em estudos de wayfinding que usam RV. Com este intuito, foram desenvolvidas duas interfaces de navegação para Realidade Virtual (i.e., Balance Board e Walk-in-Place), também numa perspectiva de DCU, para garantir um constante ciclo de testes e aperfeiçoamento das implementações junto dos utilizadores. Foi realizado um estudo comparativo entre estas duas interfaces de navegação e uma outra que é utilizada mais frequentemente em estudos com RV (i.e., um Joystick). Este estudo comparativo realizou-se num contexto de avaliação da consonância comportamental com avisos de segurança e foram analisadas variáveis de desempenho, assim como os níveis de presença das diferentes interfaces de navegação. Não se observaram diferenças estatisticamente significativas em relação aos níveis de presença nem em relação à consonância comportamental entre as três interfaces de navegação. No entanto, foram encontradas diferenças estatisticamente significativas em várias variáveis de desempenho (e.g., velocidade média, distância percorrida). Também são discutidas as possíveis linhas de investigação de continuação ao trabalho.

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Chapter I - Introduction

This study is carried out in the scope of the use of Virtual Reality (VR) for Ergonomics studies, in the domain of Cognitive Ergonomics to be applied in the optimization of Human interaction in Design proposals.

The International Ergonomics Association (IEA) defines Ergonomics as having three domains of specialization (IEA, 2006): 1) Physical Ergonomics; 2) Cognitive Ergonomics; and 3) Social or Organizational Ergonomics. Physical Ergonomics concerns with the human physical compatibility with the static and dynamic parameters of physical work. Cognitive Ergonomics concerns with the mental processes when relating the human interactions with elements of a system. Social and Organizational Ergonomics concerns with the optimization of work systems (organizational structures, policies, processes).

Since the common denominator of the three domains is Human Behavior, its assessment is considered the golden measure for the evaluation of efficiency of the solutions (e.g., warnings, environments). However, this assessment is complex due to the costs of effort, time, safety, and ethical considerations involved in measuring what people do, without biasing their behavior and offering a realistic situation/context for interaction, with a good balance between internal and ecological validities. This fact has led researchers to choose to measure other variables, other than behavior, in order to test the quality of the solutions (e.g., attention, comprehension) and resort to methods and tools such as questionnaires, self-reports, among others (Duarte, Rebelo, & Wogalter, 2010). In this sense, VR has been considered a methodological tool with the potential to carry out this type of studies, allowing the assessment of human behavior, minimizing or overcoming the majority of the obstacles identified in the so-called “traditional” methodologies, with a reasonable ecological validity (e.g., Blascovich et al., 2002; Duarte et al., 2010).

However, despite recent technological developments, there are not ready-to-use VR solutions that are suitable for this type of studies which enable researchers with an easy customization of variables that they want to evaluate (e.g., behavioral compliance). Furthermore, current systems are not without limitations with some of the most important connected with navigational interfaces which, in many cases, offer navigation forms that are not “natural”, which can jeopardize the validity of the study.

In this regard, the main objective of this study is the determination of the factors that influence VR-based studies and create a VR model, which can be customizable and dedicated to the study of human behavior for Cognitive Ergonomics studies. To achieve this objective, the following specific objectives were defined:

- Develop and evaluate a VR model for Behavioral compliance with warnings studies and for Wayfinding studies, using a User-Centered Design (UCD) (ISO, 1999) approach;

- Develop navigational interfaces to use in the VR model and evaluate it for Cognitive Ergonomics studies.

Due to the multidisciplinary nature of VR, it would be impractical to focus in several of the sub disciplines (e.g., hardware, software, interaction strategies, sounds, virtual environments, storytelling, data collection location, variables of the study) with the level of intended and necessary detail and as such, the main focus was given to the software sub discipline. Although the level of expertise regarding the remaining sub disciplines is lower than for the software, the model was developed to be compatible with all of the sub disciplines.

The methodology used for the development of this work is presented in Figure 1. It is divided into three stages.

On Stage 1, the main development of the ErgoVR system took place, which will be further detailed on Chapter II - Model Development (ErgoVR). Initially, from the information gathered from a Literature Analysis and the User's needs, the definition of requirements took place. From those requirements the development stage ensued, followed a testing stage. These three stages are part of an iterative cycle (i.e., based on a UCD approach), where the requirements and consequently the development stage had some refinements and improvements. When the ErgoVR system was at a stage that was considered to follow the requirements and the tests ran as expected, the first version of ErgoVR was built before entering in Stage 2.

Stage 2 represents the evaluation made of ErgoVR, with two main studies. This evaluation is detailed in topic 2.4 - Evaluation of ErgoVR. The studies focused on the assessment of human behavior in the interaction with warnings (i.e., evaluation of behavioral compliance with warnings) and complex environments (i.e., wayfinding performance evaluation), in everyday and emergency situations. Although not represented in the diagram, some minor changes occurred at this stage which resulted in the second version of the ErgoVR system.

On Stage 3, the development of the Balance Board and Walk-in-Place navigational interfaces and the experimental study to evaluate them for Cognitive Ergonomics studies, takes place. The development approach used was the same as the one for the ErgoVR system, i.e., UCD. This allowed that the development of the interface was accompanied with constant testing and improvements until it was deemed ready for a more complex test. At that point, an experimental study (detailed on Chapter III - Navigational Interfaces) was done. Since one of the main objectives of conducting this study was to evaluate the navigational interface while comparing to other navigational interfaces, on a Cognitive Ergonomics context, an already available Virtual Environment (VE) and scenario was used. The study had a between-subjects design due to the repetition of the task, in the same VE, measuring performance variables which would be affected by the learning effect of if there were repetition. Its focus was on the evaluation of behavior compliance with warnings in an emergency situation. From the development of the Walk-in-Place interface and the experimental study's results, the most recent version of the ErgoVR was made. Future work on ErgoVR should continue from this version.

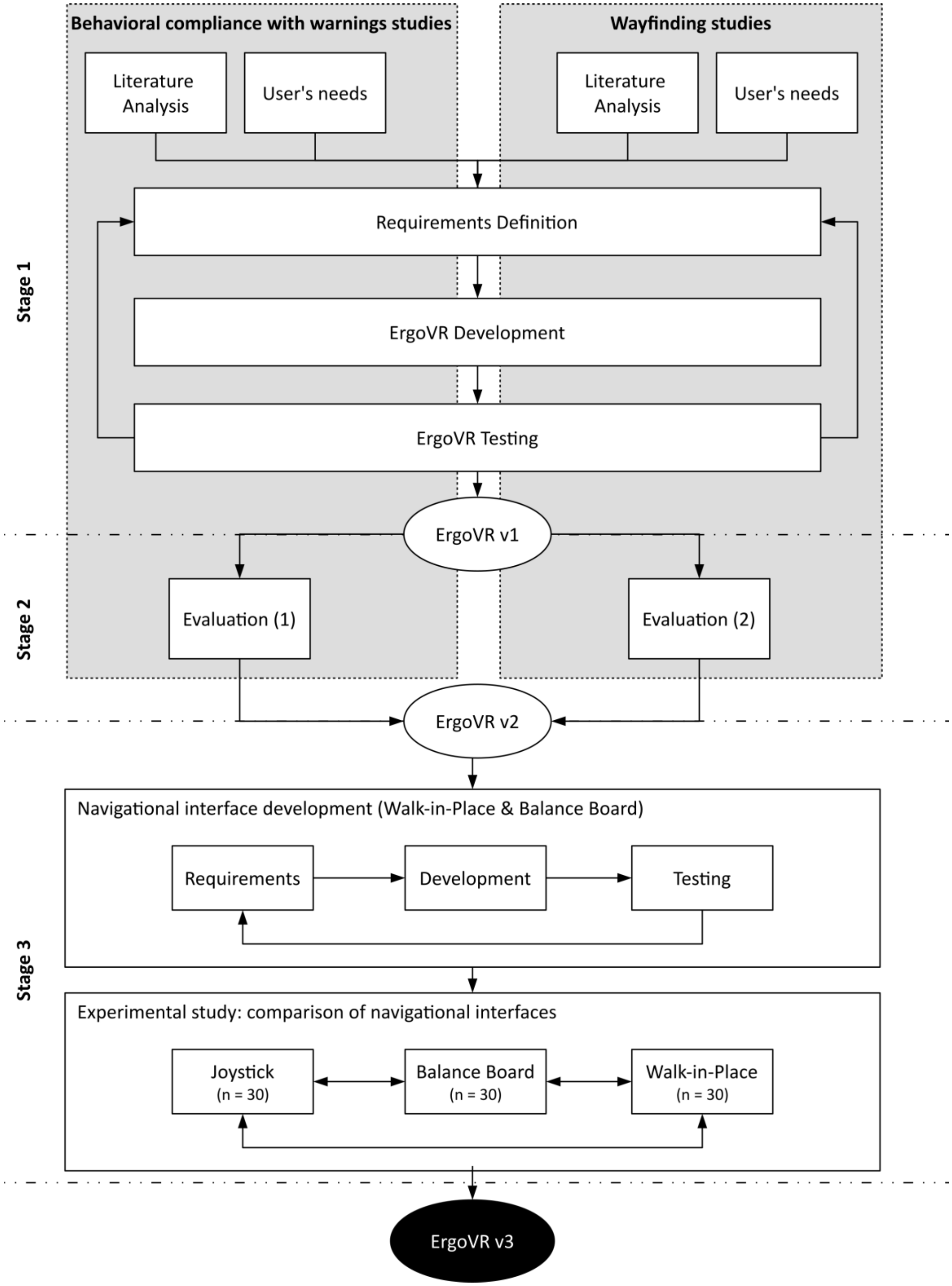

Figure 1 - Diagram of the methodology used

1.1 Virtual Reality and Ergonomics Research

In the literature, Virtual Reality is defined on two main points-of-view that complement each other. One is focused on the concept of VR (e.g., Burdea & Coiffet, 2003), while others focus on the technological side of VR (e.g., Gutierrez, Vexo, & Thalmann, 2008; Steed, 1993).

Burdea and Coiffet (2003) defined VR as a group of three concepts: Interaction, Immersion and Imagination. Interaction is the ability of a VR system to allow interaction with the VE (e.g., holding, moving objects, walking). Immersion is the isolation degree to which the individual is, to the extent of the real world that surrounds him. Imagination is the ability or willingness of the individual to believe that he/she is inside the virtual world.

From a technological point-of-view, VR can be divided into three main categories: non-immersive, semi-immersive and fully-immersive. Each category is defined based on its ability to isolate the user of the VR system from the outside world. As such, a non-immersive VR system is a system that provides minimal isolation from the outside world (e.g., a computer screen). A semi-immersive VR system provides increased immersion by using bigger screens (e.g., 3D projection). Fully-immersive VR systems are those that try to isolate the user from the outside world. Examples of fully-immersive VR systems are CAVEs (Cave Automatic Virtual Environment) or systems that use Head-Mounted Displays (HMDs).

Barfield and Weghorst (1993), presented another VR-related concept called sense of presence. The sense of presence is a subjective measure, given by the users that interact with the VR system. It represents the extent to which users believe that they are somewhere different to their actual physical location.

Virtual Reality allows the creation of a diverse variety of contexts of study. It allows to interact with dangerous environments and emergency situations while assuring the safety of the user of the VR system. Also, VR allows to replicate studies in a systematic and economical way. Regarding the data, it is possible to collect automatically, rigorously and efficiently data on the complete interaction which might have been difficult in real settings. The technological advances and reduces costs associated with VR equipment makes it more accessible for laboratories, even with low budgets.

Nonetheless, VR has its disadvantages, such as the realism level of VEs. This is due to the amount of information that is required to be processed in real-time for rendering and processing of the interactions with the equipment. On the navigation and interaction devices, they are currently limited, expensive and they can be intrusive (e.g., haptic force feedback devices). Current VR devices can cause physical fatigue to the user, due to its intrusiveness (e.g., heavy, uncomfortable, limit the movement). With HMDs, there is also the possibility of ocular fatigue due to the proximity of the screens to the eyes. However, one of the main disadvantages of VR is simulator sickness which can affect with more severe symptoms a small percentage of users to an extent where they have to stop the experiment (Cobb, Nichols, Ramsey, & Wilson, 1999). Simulator sickness can be caused by several factors, such as: the latency of image presentation (or delay between an action in the real world and the corresponding action in the VE), contradictory perceptive clues, among others.

Nonetheless, VR has the potential to be used to carry out different types of studies by minimizing or overcoming the majority of obstacles found in the “traditional” methodologies while still maintaining a reasonable ecological validity. Its advantages are compelling to use it as a tool for research, especially in Ergonomics.

Virtual Reality is of interest to Ergonomics to understand how people interact with the VEs, to improve said VEs, and also to use VEs in ergonomics analysis and design (Wilson, 1997). Work has been done on the side and after effects of using a VR system, the appropriateness of its hardware and software as well as the understanding of factors related with the participant’s performance (Wilson, 1999).

Furthermore, some studies have used VEs as a simulation tool in various contexts and for different purposes, such as for example: fire safety studies (e.g., Kinateder et al., 2014; Ronchi et al., 2015; Xu, Lu, Guan, Chen, & Ren, 2014); training, for example in safety (e.g., Grabowski & Jankowski, 2015; Schwebel, Combs, Rodriguez, Severson, & Sisiopiku, 2015) or medical procedures (e.g., Abelson et al., 2015; Arora et al., 2014); warnings simulations (e.g., Duarte, Rebelo, Teles, & Wogalter, 2013; Glover & Wogalter, 1997); wayfinding (e.g., Omer & Goldblatt, 2007; E. Vilar, Rebelo, Noriega, Teles, & Mayhorn, 2013); among others.

Despite the large amount of studies already made with VR, interaction with VEs is still not completely natural (Wilson, 1997) because there is still a need of the use of sensors and other input devices and limitation of force or haptic feedback. Although the panorama is better at the moment than it was some years ago, and improvements were made in that regard (e.g., LeapMotion[1], CyberGrasp[2]) it still warrants further research on interaction devices. As mentioned earlier, a focus on navigational interfaces was given in this study, where the rationale behind the decision is detailed on Chapter III - Navigational Interfaces.

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[1] LeapMotion is a device that can detect the movement of the hands and allows to introduce interaction in VR (more information can be found on the official website: www.leapmotion.com)

[2] CyberGrasp is a force feedback glove for VR that allows the user to have some haptic feedback (i.e., force) when interacting with objects in the VEs.

1.2 Structure of the document

This document is divided into four chapters. The current chapter presented a brief general introduction to the context of this research. Chapter II - Model Development (ErgoVR) details the methodology used in the development of the ErgoVR system. It also describes the requirements that are valid for Cognitive Ergonomics and Physical Ergonomics studies as well as other studies which are reflected in terms of functionalities of the ErgoVR system. In that chapter, the description of the ErgoVR system is also given. Regarding the evaluation of the ErgoVR system, some case studies are also presented that used the ErgoVR system as a tool.

Chapter III - Navigational Interfaces presents the development of the navigational interfaces to use in the VR model to evaluate it for Cognitive Ergonomics studies. A comparison study was made in a behavioral compliance with warnings context, while comparing some performance variables between three navigational interfaces.

Finally, Chapter IV - Final Conclusions presents the conclusions of the research, its limitations as well as future work directions.

Chapter II - Model Development (ErgoVR)[3]

2.1 Introduction

As mentioned in the previous chapter, a necessity for a Virtual Reality (VR) system presented itself, to use in Cognitive Ergonomics studies.

Behavioral evaluation studies can use VR which is a tool that can replace conventional methods of research such as observation of behavior in natural settings (e.g., Drury, 1995; Westbrook, Ampt, Kearney, & Rob, 2008). The main disadvantages of these methods are that is not ethical to place an individual in hazardous situations for research purposes and the development of believable experimental scenarios is difficult and has usually high financial costs associated. Virtual Reality has the possibility to overcome, or minimize, those limitations.

Although some studies use VR to evaluate human interaction, for example with safety signs in emergency evacuation studies (e.g., Ren, Chen, & Luo, 2008; Smith & Trenholme, 2009; C.-H. Tang, Wu, & Lin, 2009), it is not evident the use of a system that collects, in an automatic manner, data related with human interaction that can be used for Ergonomics studies. Commercial VR solutions (e.g., Virtools, WorldViz Vizard), although they can be integrated with different hardware equipment, do not allow data collection of human interaction without the development of additional software. Moreover, they are quite expensive solution when taking into account most of the research budgets.

Designing effective VR systems poses a number of problems. One major question is the tension created between the research needs and the budget, available equipment, as well as the engineering response. In other words, one thing is the need to create a Virtual Environment (VE) that is able to produce the desired behavioral responses in the study's participants; another thing is the ability to create, with the available resources and the established time, a VR system that respond to the research goals.

As such, the ErgoVR system was considered to be developed to better attend the different studies' needs, by having more control in its development. With this in mind, three main objectives were defined: (1) the system must be developed by involving the users (i.e., researchers) to better attend their specific needs and limitations; (2) the system must be able to automatically collect data regarding behavioral compliance in different scenarios; and (3) the system must be easy to use since it will used by people from other fields than computer

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[3] Parts of this chapter are from the following paper "Teixeira, L., Rebelo, F., & Filgueiras, E. (2010). Human interaction data acquisition software for virtual reality: A user-centered design approach. In D. B. Kaber & G. Boy (Eds.), *Advances in Cognitive Ergonomics. Advances in Human Factors and Ergonomics Series* (pp. 793–801). Miami, Florida, USA: CRC Press/Taylor & Francis, Ltd."

engineering, i.e., without the need of programming from the part of the researcher that wants to use the system as a tool for the project at hand.

Since one of the main objectives was to develop the system involving the potential users throughout the development process, the system was developed in a User-Centered Design (UCD) perspective accordingly to the ISO 13407 standard (ISO, 1999). As said by Kontogiannis and Embrey (1997), the system was not designed only for the users but with the users.

As such, this chapter describes the development of the system and details the individual parts of that system, i.e., a VR pilot facility, a VR simulator and the corresponding data exporting application. In topic *2.2 - Method*, the UCD perspective used and the first iterative cycles on the development of the ErgoVR system are described. In topic *2.2.2 - Requirements*, details are presented regarding the requirements for the ErgoVR system in general as well as more specific requirements for studies about behavioral compliance with warnings and wayfinding. Further, on topic *2.3 - Description of the ErgoVR system*, the system is detailed in terms of the components that are part of it as well as the features that the system currently has to fulfill the requirements set. Before finalizing with the chapter with some conclusions, topic *2.4 - Evaluation of ErgoVR* presents cases studies in the fields of behavioral compliance with warnings and wayfinding, as well as other studies, where the ErgoVR system was used.

2.2 Method

As mentioned before, in order to involve the potential users throughout the development process, an UCD approach was taken in the development of the ErgoVR system. User-Centered Design relies on an iterative process (see Figure 2) to involve the participation of the potential users in the design decisions. The potential users can express the difficulties they encountered during the interaction with the prototypes that were produced in each iterative cycle. In the earlier stages, users may be involved in the evaluation of the use case scenarios or partial prototypes. As the design solutions become more elaborate, the evaluations can be based on more complete and concrete versions of the product.

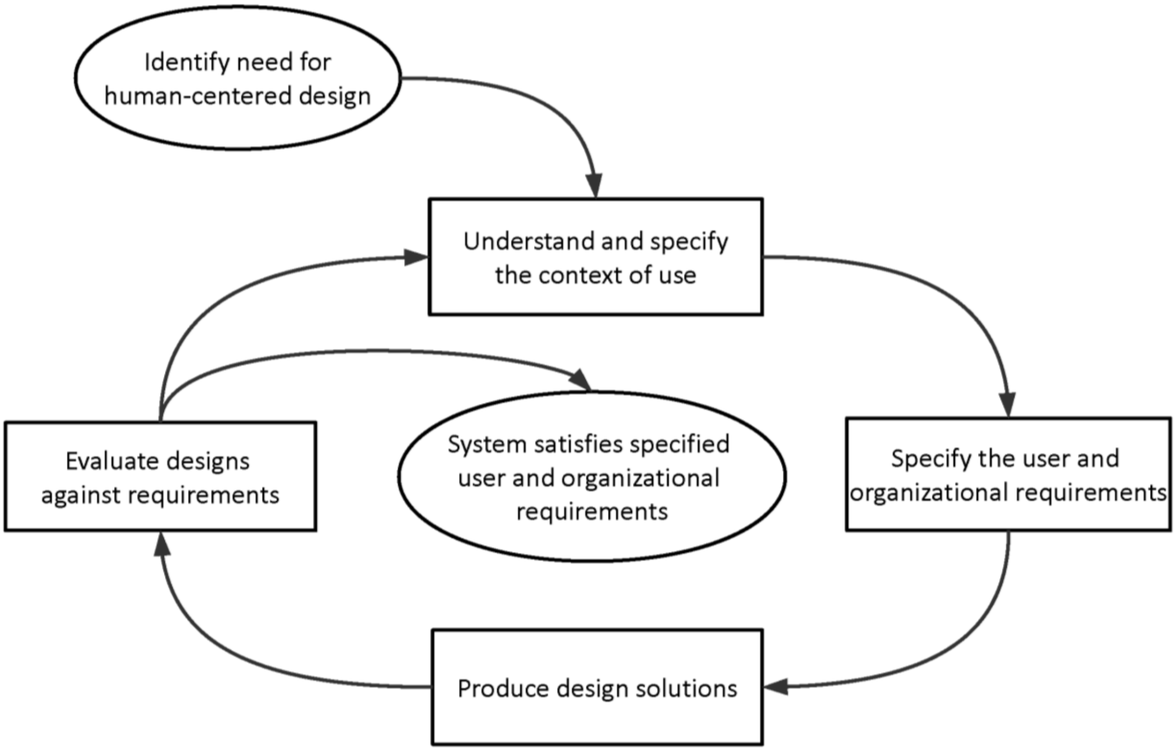

Figure 2 - User-Centered Design diagram. *Adapted from* (ISO, 1999).

User-Centered Design has been used successfully in product design (e.g., Chen, Sato, & Lee, 2009; Kanis, 1998). The process has four main stages. The process begins with the identification of the need of this process. After the need is identified, the first stage starts which is the understanding and specification of the context of use. The second stage is where the user and organizational requirements are specified. In the third stage, design solutions are produced. In the fourth stage, designs proposed on the previous stage are evaluated against the requirements. If there are changes to be made to the system the iterative cycle is completed, passing to the first stage with the new changes to be made. The cycle ends on the fourth stage when the requirements are satisfied.

The different stages of the UCD process related to the development of the ErgoVR system are detailed in the next subtopics.

2.2.1 Context of use

The ErgoVR system is to be mainly used for research works in the fields of Ergonomics to support the research community and in the development and evaluation of professional or consumer products. For the research community in Cognitive Ergonomics and Design, the ErgoVR system can help to develop studies related for example with: product interaction optimization and behavioral differences between groups defined by gender, age, education, cultural background, previous knowledge, among others, in different contexts of use. Related to the development or evaluation of products, it is possible to assess different aspects of interaction with the product, including emotion, perception, and cognition, among others.

The system is to be used in a University environment where activities such as teaching, research, and scientific and professional community support take place.

In two brainstorming meetings and informal meetings, six specialists with expertise in the fields of Ergonomics, Engineering, Psychology, Design and Architecture, outlined the context of use of the ErgoVR system. Since the context of use is given by the characteristics of the users, tasks and the physical and organizational environments, those were also defined and are as follows:

The system can be used by university students, Masters and PhD students of the courses of Ergonomics and Design but also of Engineering, Psychology and Architecture.

2.2.2 Requirements

In this section, the most generic requirements that were defined from the start of the development of the ErgoVR system will be addressed. These generic requirements were discussed and defined by the same group of specialists mentioned earlier, in three focus group and also informal meetings. The requirements were defined taking into account the overall performance and feasibility of each task in a timely manner.

It is intended that the users can use the system in a VR pilot facility, using specific hardware and the ErgoVR system, whose general characteristics were defined as:

- Characteristics of the pilot facility – Adjustable lighting so that external stimuli are minimized; adjustable temperature to have a constant temperature around 22 degrees Celsius throughout the year; and sound intensity level below 40 dB. The pilot facility must have image recording equipment to record the external behavior (e.g., body movements and facial expressions) of the participants;
- Characteristics of the hardware – Immersive VR equipment, preferably a stereoscopic solution; a computer with a graphics cards capable of present complex VEs at a constant high velocity, so that the effects of simulator sickness that the participants might experience can be reduced; motion sensors for motion capture of the body of participants; interaction devices, namely for navigation in the VEs and to interact with objects inside those VEs;
- Characteristics of the software – low cost system, preferably free for research use that can work at least on Microsoft® Windows and that it can interact with the VR equipment in the pilot facility. It also must automatically gather data about the human interaction, present and extrapolate information from that data in different formats to be analyzed and the software should also be developed considering that its users are not from the computer engineering field.

Given these generic requirements, possible solutions were presented for them and in later cycles of the UCD approach, more specific requirements were defined and that can be more directly connected with the research studies that will use the ErgoVR system.

a) Specific requirements

As with the generic requirements, several focus group meeting took place with the group of specialists. For each UCD iterative cycle there was at least one meeting to analyze the proposed solutions and the adjustment or new definition of requirements. In this topic, a more condensed view of some of the more specific requirements will be presented with the focus only on the software which is what can influence more directly the research studies.

The ErgoVR system allows that studies can evaluate participants' behavior when exposed to hazardous and/or emergency situations inside the VEs without compromising their safety. As such, the measurement and analysis of the participant's activity in an automatic manner by ErgoVR requires special attention to what is possible to detect and record regarding the human interaction within the VEs. That type of data is advantageous in several types of studies, namely in Behavioral compliance with Warnings and in Wayfinding.

As such, specific requirements were defined for the ErgoVR system to make it easier to be used as a tool for these types of studies:

- The VEs should demonstrate physical properties as in reality. For example, not crossing through walls and other objects, or a contact with a certain object should show a realistic physical reaction;
- It should be possible to collect or extrapolate, among others, the following information: participant's path and directional decisions, distance travelled, time spent in the simulation, detection of pauses (number, duration and location), areas that were most visited, among others;
- Ability to initiate specific actions depending on the participant's interaction in the VE and know when these actions happened;
- It should be possible to know when the person looked in the direction of certain objects. Without an eye-tracker integrated with the ErgoVR system it will not be possible to detect exactly where the participant looked at;
- Ability to insert fire, smoke, animations and sound in the VE, among other dynamic elements that could be necessary for the studies;
- Ability to have virtual characters present in the VEs, with controlled gestures and speech;
- To ease the use of the system, it should be based in convention so it is easy to automatize most of the procedures necessary to have a research study running.

2.2.3 Design solutions

The potential design solutions were produced using the state of art, the experience and knowledge of the participants and the results of the analysis of the context of use. Taking the results of earlier phases of the UCD iterative cycle as a starting point, the same group of specialists proposed solutions for the development of the ErgoVR system. Some of the common characteristics of the main commercial programs used for VR simulations were also taken into consideration in the deliberation of the possible solutions.

As such, at this point, more specific characteristics were defined for the pilot facility and consequently some of the expected support of the ErgoVR system in terms of VR hardware.

The pilot facility consists of a room without windows to the outside, is protected from outside noise and it can be darkened. The temperature and air quality of the room can be adjusted taking into account the season and type of use intended.

The pilot facility is equipped with the following hardware: (1) computers; (2) Head-Mounted Displays (HMDs); (3) motion sensors; (4) a VR data glove and (5) navigational interfaces.

1. There are two computers for data collection which have graphics cards from the NVIDIA® Quadro® FX family that are capable of displaying complex scenes at a constant refresh rate. They can also display in full screen a VE from the two graphics outputs. The computers are also equipped with Intel® Quad-Core processors and a minimum of 8 Gigabytes of RAM;
2. For presenting the VEs to the participant, there are four HMDs. One is a Sony® PLM-700S (commonly known as Sony® Glasstron) which is non-stereoscopic and has a horizontal field of view of 28°. The other HMDs are from Sensics[4]. All models from Sensics have stereoscopic capabilities. One of the models is the piSight 145-41b which has a wide horizontal field of view (144°) and a smaller vertical field of view (30°). The second model is the xSight, which has a horizontal field of view of 123° and 45° vertically. Both the piSight and xSight models use tiled displays, which are several micro-displays arranged in a grid to create the wider field of views. The last model is a zSight that has more limited field of views of 60° (with 100% binocular overlap) or 70° (with 75% binocular overlap). It only uses a single display for each eye, which provides more detail for certain situations (e.g., reading fine lettering);
3. For capturing the movement of the participant is possible to make use of three Ascension-Tech® Flock of Birds magnetic sensors and an XSens® XBus Kit with 10 MTx inertial motion sensors. Although the magnetic sensors are sensitive to metallic environments, they have high precision in the collected data. They have 6DOF (Degrees of Freedom) which provide the position and orientation of the sensor depending on a reference point. They also have

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[4] http://sensics.com/

a high frequency output of data (around 144Hz), as well as being usually cheaper than other types of sensors. The inertial sensors from XSens are only orientation sensors. However, they do not require a reference point and can transmit data through Bluetooth® at a rate that can be until 512Hz, depending of the number of sensors being used at a time;

4. To interact with the VE, it is possible to use a 5DT Data Glove 5 Ultra that detects the flexing of the fingers and hand of the participant;
5. The devices that can be used for navigation which are currently available are: a keyboard and mouse combination, joysticks, a 3Dconnexion SpaceNavigator 3D mouse and the Nintendo® Wii Balance Board;
6. The pilot facility has three Bosch WZ18 video cameras to record the participant's activity which are recorded synchronously with the images from the VE.

Regarding the ErgoVR system, it will be detailed further in topic *2.3 - Description of the ErgoVR system*.

2.2.4 Evaluation

For the first pilot tests to evaluate the pilot facility, hardware and the ErgoVR system, a simple scene for simulation was created. This scene consisted in a 25 x 15 meters space, with four rooms and a cross corridor that separated them. Each room was around 9.5 x 6 meters and had a different theme associated (reception desk, meeting room, waiting room and an office). A top view of the environment can be seen in Figure 3.

Figure 3 - Top view of the Virtual Environment used for the first pilot tests

There were five participants in the pilot tests and they were told to explore the environment freely between 5 to 7 minutes. During each simulation, the ErgoVR system was collecting data automatically for later analysis. The main objective of these pilot tests was to assess if the ErgoVR system was working properly in the presentation of the VE, the accuracy of the data collection and proper interaction with the VR devices. As such, after the simulation, each participant was asked for commentaries, suggestions and for difficulties encountered during the simulation.

With the outputs from the ErgoVR system and the results from informal interviews with the participants, the same group of specialists had two meetings to analyze the data and propose modifications to the system for the following UCD iteration cycle. With the information generated after the meetings, changes were made to the system to correct some of the problems found by the participants and by the group of specialists.

Some examples of the required changes are to have the possibility to control the sensitivity of the navigational interface (a joystick at this point), to have the possibility to interact with certain objects in the VE and also to have the possibility to observe the path that the participant did in a top view manner to ease the subjective analysis.

After the changes made, a new set of tests were performed, in the same conditions of the pilot tests mentioned earlier (five participants and post-simulation interviews). The difference from the previous tests was that buttons were added to the environment and it was now possible to interact with them in order to perform some actions.

At the end of each cycle of the iterative process, the implemented solutions are always considered against the requirements and the results obtained from pilot tests (which are done at the final step of each cycle of the UCD). With the considerations resulting from this step new changes and requirements to the system are generated.

2.3 Description of the ErgoVR system

ErgoVR is a software-based VR system that was created as a VR model Behavioral compliance with warnings studies and for Wayfinding studies, using a User-Centered Design (ISO, 1999) approach. Although the main focus for the development of the ErgoVR system was for these types of studies, the system was also developed with an openness of allowing other types of studies. This was done by trying to generate features in the system that would be sufficiently generic that several types of studies could benefit from the features.

The ErgoVR system is composed by two separate applications to fulfill the needs of research studies: (1) simulator; and (2) log viewer. The main purpose of the simulator is to be able to simulate a study's scenario with its related VE and provide the necessary interactivity between the participant and the VE by using different VR equipment (e.g., Head-Mounted Display, headphones, motion sensors, among others). The log viewer's main purpose is to allow the researcher to analyze and export the data collected during the simulation.

Both ErgoVR applications were completely developed by the author of this document, as well as all the necessary engineering decisions made to fulfill the requirements that were previously defined.

In the next topics, the ErgoVR system will be explained, taking a perspective of a researcher that wants to start a new research project and wants to use this system as a research tool. As such, the following topics focus on the features and capabilities of the ErgoVR system and how they fulfil the requirements defined, rather than focusing on the engineering point of view of the development of the ErgoVR system.

2.3.1 Global view of the system

The use of the ErgoVR system spans throughout different decision points of a research project. This happens because the scope of the ErgoVR system is vast in a research project, i.e., from the initial decisions of the main objectives of the study to the more specific details of how and what should happen during the simulation. Some of the decisions that need to be made for a research project will change the way a researcher interacts with the ErgoVR system and in a similar manner, due to the capabilities of the system and how they are used, the ErgoVR system can affect certain decisions of a research project.

For the reason that the use of the ErgoVR system encompasses different stages of a research project, as well as that the system should be usable for researchers that do not necessarily have the technical skills to add certain behaviors programmatically, it was decided that the ErgoVR system should work based on a model of pre-defined conventions of use. Although this model might, in some sense, inhibit some control over what can be personalized (only for those without the necessary technical skills), it provides a plethora of features that can fulfill the needs of different types of research projects (with a focus on behavioral compliance with warnings and wayfinding studies).

The process of using the ErgoVR system for a research project can be divided into three main stages (see Figure 4). First the VE needs to be conceptualized and created according to the requirements of the study at hand. After that, the created VE will be passed to the Simulator for the data collection stage. The recorded files from the data collection stage are then passed to the *LogViewer* for the data analysis stage.

This topic will describe generically how these elements work with each other, by describing: the concepts and conventions used in the creation of VEs; the features and functionalities of the simulator and; how the researcher can analyze the collected data using the *LogViewer* application. In each subtopic, features and functionalities that are specific to behavioral compliance with warnings studies or wayfinding studies are mentioned as such. Other features and functionalities presented in those topics are generic and can be applied for other types of studies.

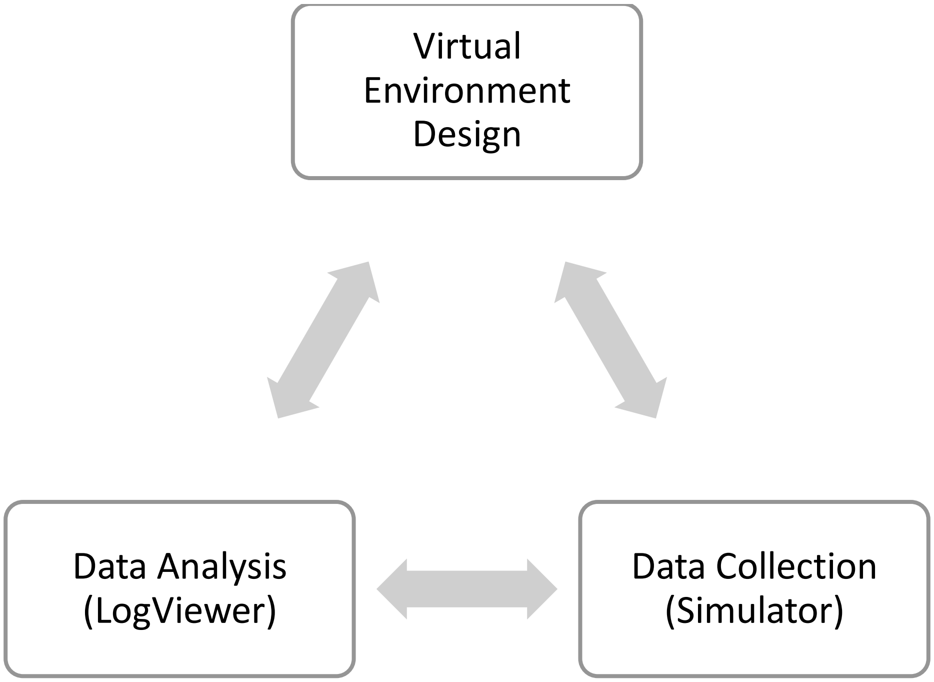

Figure 4 – The three stages of the ErgoVR's system use

The following topics will present the ErgoVR system taking into account the perspective of a researcher wanting to use it as a tool for a new research project. As such, the topics are separated into the three moments described earlier. In each one of the moments, the description of the features and capabilities of the associated part of the system are described independently. Most of these features and capabilities were created to fulfill the requirements presented in earlier topics. However, the solutions achieved for some of the requirements span over more than one stage. This will be addressed by presenting the features that cover a certain requirement for each stage separately, being the requirement presented repeatedly in the associated stage.

2.3.2 Creation of Virtual Environments

This topic describes briefly how VEs should be created to be used in the ErgoVR system.

Virtual Reality presents VEs in real-time, creating therefore a necessity of certain attention while modeling a VE. Unlike other type of 3D modeling where a render can take several hours, in VR, a scene is presented at 60 frames per second, i.e., 60 renders per second. As a consequence, to be able to render a scene at that speed, some compromises have to be made, and usually they are in the level of detail that is possible to give to a scene, its objects and materials.

The level of detail that a VE can have can be compared with what a game environment can provide up to a certain extent. A game, like in VR, needs to render at 60 frames per second. Nonetheless, in the last years it is possible to observe that the graphic quality of games is increasing considerably fast. This is possible due to the graphics cards becoming more powerful each year, with enough power to process more detail in real-time. As such, and because of this similarity with games, the environments for VR can use the same techniques that are commonly used for games. These techniques improve the visual quality of an environment to be rendered in real-time at a low computation cost. Since it is not the main scope of this document to provide a more detailed description of these techniques neither their implementation, please refer to the book “Real-Time Rendering” (Akenine-Möller, Haines, & Hoffman, 2008) for further detail. A detailed explanation (and tutorials) of some of the game techniques (e.g., bump mapping, UVW mapping) that can be applied to VR that work with the ErgoVR system are presented in (Fernandes, 2013).

The ErgoVR simulator can open and present VEs in the DotScene format. The DotScene format is a standardized XML (eXtensible Markup Language) file format made for OGRE (Object-Oriented Graphics Rendering Engine). The DotScene format presents, hierarchically the relationships of all the objects that belong to a scene. These objects can be from normal, 3D visible objects, to other elements such as cameras, lights, materials used, animations, triggers, among others.

As such, the scene itself can be modeled in any 3d modeling software (e.g., Autodesk® 3ds max, Autodesk® Maya, Blender) providing there is an available plugin capable of exporting the scene to the aforementioned DotScene format. In the Ergonomics Laboratory, the tools that were most used are Autodesk® 3ds max 2009 for the 3D modeling and scene creation and the OgreMax v2.1.2 plugin to export to the DotScene format. Another solution used to export the scene is using the EasyOgreExporter plugin, with Autodesk® 3ds max. Although there are slight changes in the DotScene file exported by both plugins, the ErgoVR system supports both (the latest version tested of EasyOgreExporter was v1.9).

Since one of the main requirements for the ErgoVR system was that it should be usable by people from other fields (e.g., Design, Architecture), meetings were made, in the different iterations of the development, to establish conventions to be used in the creation of VEs in order to be possible for the ErgoVR simulator to interpret and present those VEs without requiring additional human intervention. These defined conventions have a small level of impact of additional work for the person that is creating the VE and at the same time allow a higher level of control of the actions that will happen during the simulation.

Most 3D modeling software provide the possibility of creating dummy objects (or empty objects), which are elements that have no visual representation, yet have the basic components of an object, i.e., they have a position and an orientation, as well as may have children objects associated with them. As such, these elements (i.e., dummy objects) may be used to define the VE's hierarchal structure, which in turn will facilitate its automatic processing by the simulator.

The base template for the creation of VEs to be used in the ErgoVR system is composed of a set of dummy objects with the following pre-defined names: 1) Static; 2) Movable; 3) Boxed; 4) NoPhysics; 5) ObservableObjects; and 6) Events. The Events object has two direct children: 6.1) Triggers; and 6.2) Actions.

This template will force the VE modeler to create a structured approach when creating the VE (which most likely already had) allowing at the same time to focus on the interaction outcome of the VE, without the intervention of more specialized elements of the team. The first four items of the template are related with the physics of the VE. Any object that is a children of the dummy object Static, will be considered as a static, fixed physical element that cannot be crossed over or moved. If there are elements that are intended to move and have natural physical reactions to collisions, they should be placed as children of the Movable dummy object. For more complex objects (i.e., complex forms that are not basic primitives) and where the type of interaction that is intended with them is low (i.e., only to check if there's a collision), it is advisable to place those objects as children of the Boxed dummy object. This will have two effects: 1) An invisible physical box will be placed that contains the object inside; and 2) since it is a simpler physics object, it will ease the necessary calculation work on the Physics system, which will improve performance of the simulation. Following the same reasoning, there might be some objects that the participants will not be able to interact. As such, those objects should be under the *NoPhysics* dummy object, which will tell the simulator to not generate physical elements for those objects. The dummy object *ObservableObjects* is for objects that are intended to know if participants of the study looked at (i.e., the center of the screen, until an eye-tracker system is integrated into the simulator).

The Events dummy object and its direct children objects Triggers and Actions are where objects related with the events in the VE should be placed. 3D modeling software usually allows to add extra textual information to an object. Using that feature of the software, the Events dummy object is where the VE modeler should place the information that defines the association between the triggers and actions. More details regarding this subject are presented in the description of the *Event System* in topic *2.3.3 - Simulator*. The events and respective actions need to be defined, and therefore need to be fully considered, at the design time of the VE to fulfill the specific study's objectives, i.e., when the scenario with the context is being defined. By defining the events and actions at the design time, the VE modeler is encouraged to follow the best practices of testing early and often.

The initial position in the VE of the participant is also an important aspect and how that could be achieved in an easy manner by the VE modeler. As such, it was defined that creating a Camera with the name “StartPosition” would determine that initial position. The rotation and the point where the camera was looking at are also adopted automatically by the ErgoVR system.

Another important aspect of the creation of VEs is the necessity, for certain studies, to have virtual humans present in the VE. As such, certain considerations should be taken into account while developing virtual humans to use in VEs for the ErgoVR system. The simulation of virtual humans is an immense challenge requiring solving many problems in various areas (Magnenat-Thalmann & Thalmann, 2004). Some of the challenges pass through: having a good representation of faces and bodies; having a flexible motion control to reproduce motion naturally; for autonomous virtual humans it is required to be able to reproduce a high-level type of behavior that is plausible and believable; the virtual humans should be able to have and present emotional behavior; having a realistic appearance in terms of hair, skin and clothes; being able to interact with the VE in a natural way (i.e., by interacting with other virtual objects or by having social exchanges with other virtual humans); and being aware of the presence of the actions of the participant and acting accordingly (e.g., deviating from the participant, looking at the participant if looked at).

At this moment, the support for virtual humans in the ErgoVR system is limited in a way that only allows to have virtual humans with pre-defined behaviors which are represented by animations (body and face) and the use of sounds (e.g., to represent someone speaking). There are several 3D human modeling software available (e.g., Smith-Micro Poser[5], DAZ Studio[6], MakeHuman[7]) that allow to create a virtual human, where it is possible to change different features of a person (e.g., age, gender, race, height, weight) and also create body and facial animations. Depending of the software used, facial animations can also be associated with speech sounds.

Also regarding the 3D human modeling software, it is possible to export the virtual human as a low-polygon mesh and already rigged for animation to be imported in 3D modeling software, which is appropriate to use in settings where it is required rendering at high rates, such as in VR.

As such, the process to create virtual humans to be included in VEs goes by using one of the available 3D human modeling software and define there the intended characteristics of the virtual human (e.g., gender, height, clothes). After that, the animations necessary for the study at hand should be defined, including facial animations for speech simulation if required. After that, the virtual human should be exported to be included in the VE. For that, a low-polygon mesh should be used and it should also include the rigged animation skeleton. In the 3D modeling software, the virtual human should be imported and placed inside the VE in the desired location. It is in this moment of the process that the modeler should pay attention if the animations were

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[5] http://my.smithmicro.com/

[6] http://www.daz3d.com/

[7] http://www.makehuman.org/

imported correctly and also the modeler needs to associate each animation with a speech sound and the moments when they would play in the VE. This should be done in the format expected by the Event System, described in more detail in next topic (2.3.3 - Simulator). For more details, with a full tutorial on how to create virtual humans to be used in the ErgoVR system, please see (Vital, 2012).

Even though the creation of VEs was only briefly summarized in this topic, since it is not the core focus of this research work, it is clear that it is a discipline that requires detailed knowledge of several different fields, which can only be possible in a multidisciplinary team with members that have the needed expertise. It is also a task that requires extreme detailed planning and time for its development.

2.3.3 Simulator

In this topic it is described the Simulator component of the ErgoVR system. The focus presented is in terms of the features and functionality of the simulator and how they connect to the requirements presented earlier in topic *2.2.2 - Requirements*. First it will be presented a global view of the system and a brief description of the modules that compose the ErgoVR simulator. Next, the custom built modules are described in detail. The topic finishes with an overview of the currently compatible hardware that can be used with the ErgoVR system.

a) Global view of the simulator

The ErgoVR simulator is made by several subsystems as it can be seen in Figure 5. Some of the systems are composed mostly by free and open-source code libraries with a small amount of custom code. The exceptions are the *Configuration*, *Log*, *Events* systems and the main ErgoVR application which were custom developed in its entirety and resulted in the final simulator. The ErgoVR system was developed over the Microsoft® .NET Framework using C++/CLI and C# (C sharp) programming languages. At this moment, the ErgoVR only works on computers with Microsoft® Windows installed. This decision was made because of the nature of the software being developed, which has similar requirements as a video game, and because Microsoft® Windows is the only operating system with better support for the underlining graphics systems that is mostly used for games (DirectX). In the beginning of the development of the ErgoVR system, DirectX was much more advanced than the OpenGL counterpart (also used in Windows, but mostly used in Linux and Mac), which would limit the type of visual information that could be placed in the Virtual Environments that would be developed for the studies. Also, the support from the VR equipment used was mostly Windows-centric which also weigh in the decision. Despite these reasons, there are plans to make the ErgoVR work with the Mono[8] project (which

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[8] www.mono-project.com

is an open-source implementation of the .NET Framework) in the future, which would also work in Linux and Mac computers.

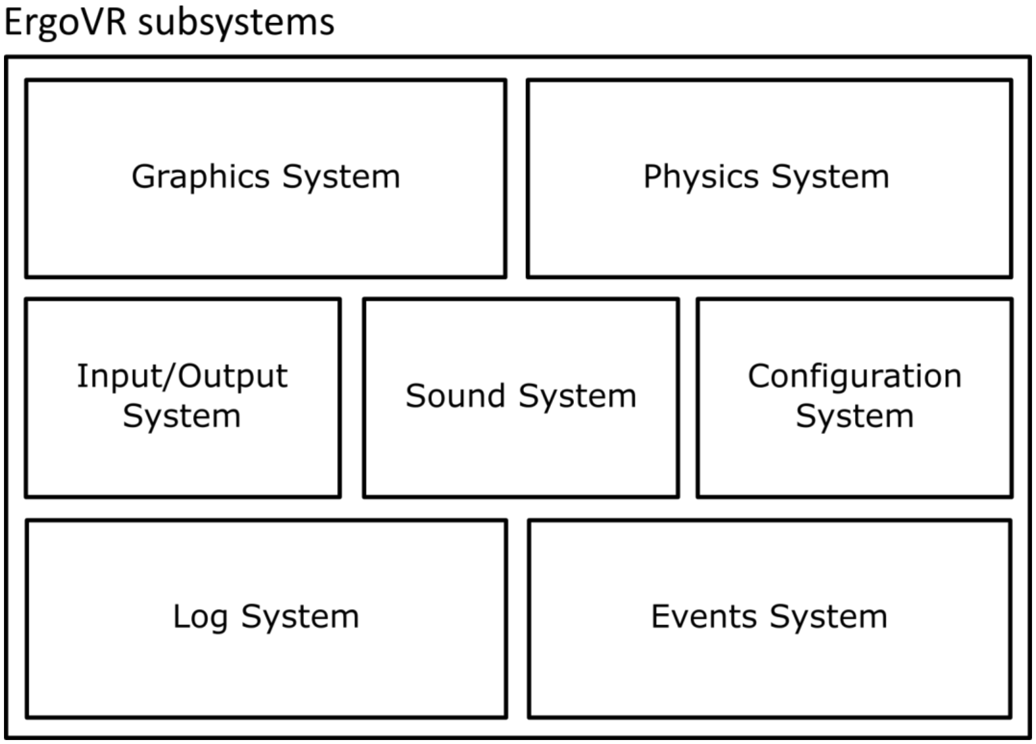

Figure 5 - Diagram with the subsystems that compose the ErgoVR simulator

The subsystems are: (1) graphics engine; (2) physics engine; (3) sound engine; (4) input/output system; (5) configuration system; (6) log system; and (7) events system.

1. The graphics engine is responsible for presenting the VE to the participant. This system loads and keeps tracks of all the elements of the VE so it can transmit the resulting image (i.e., render) to the Input/Output system to be presented in the output device that is being used at the moment. At the moment, it uses the Object-Oriented Graphics Rendering Engine (OGRE[9]) v1.7.3 library in its core. The OGRE library is a full-featured graphics engine which can present different types of visual effects and it is also able to load complex scenes with low processing requirements;
2. The physics engine is responsible for the detection of collisions with objects and introduces physical behavior to the objects within the VE (e.g. if the user collides with a ball inside the VE, the ball will roll with the appropriate speed depending on the force applied in the collision). At the moment, this system is the Newton Game Dynamics[10] v1.35 physics engine which is able to represent physical interactions between objects with a high level of control and realism;

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[9] http://www.ogre3d.org/

[10] http://newtondynamics.com/

3. The input/output system creates a bridge between the hardware's input (e.g., position/orientation of the motion sensor) and the simulator to create a response according to the data received (e.g., activating a button in the VE). The result is presented in the output devices accordingly;
4. The sound engine is responsible by presenting to the participant, sounds with effects such as 3D origin of the sound, occlusion and obstruction by objects. The sound can be presented to the participant in a headphone set or in speakers. This system uses the MogreFreeSL[11] sound library;
5. The configuration system is responsible for the reading the configuration files and configure the simulator accordingly; This system will be detailed further in a subsequent topic;
6. The event system is responsible for detecting when the participant triggered certain pre-defined events and activate the corresponding actions associated with them (e.g., a participant interacted with a door, activating therefore an animation of the door opening). This system will be detailed further in a subsequent topic;
7. The log system is responsible for recording data automatically. The data recorded are the participant's position, orientation of its field of view and occurred events during the simulation (e.g. collision with some object, activation of a trigger). This system will also be detailed in a subsequent topic.

State model

The simulator was developed considering the possibility of having different states when running. Each state represents a running mode for the simulator. These states would be created as extensions of use of the simulator's native capabilities where certain capabilities could be activated or not.

At this moment, the ErgoVR system has the following states: (1) Free Mode; (2) Normal Simulation; (3) Decision Taking; (4) Decision Taking Simulation; and (5) Walk-in-Place Simulation. All states have scene loading capabilities as well as basic support for Mouse and Keyboard movement which controls the main camera. Also, each state begins with the default configurations for translation and rotation speed defined in the configuration file.

Free state

The Free state was created to be used as a testing mode. This testing mode is usually to verify if the VE is being presented as intended. This mode does not have the Physics subsystem activated and it only accepts Mouse and Keyboard input for navigation. Also, there is no support for motion sensors or Head-Mounted Displays. In this state it is possible to navigate freely within the loaded VE.

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[11] http://www.ogre3d.org/tikiwiki/MogreFreeSL

Normal Simulation state

The Normal Simulation state is the most complete state in term of features at the moment. It is the default state for simulating VEs in the ErgoVR system since it is the state that is used in most studies at the Ergonomics Laboratory. When following the conventions set for the creation of VEs described earlier, this state has a set of native features (which are configurable) that are expected in a simulation such as: physics support (i.e., to have life-like physics interactions in the VE), navigation support in different devices (e.g., mouse and keyboard, joystick, 3D mouse), support for motion sensors (e.g., allowing to have a motion sensor to track the movements of the head and reproducing the change of perspective movement in the VE), multiple visualization outputs support (e.g., computer screen, Head-Mounted Displays or a projection), sound support (i.e., being able to play sounds), data recording (i.e., record the actions that the participants made while interacting with the VE) and also activation of the events that are associated with the VE.

Other states can be derived from this one with some of these functionalities altered to comply with the specific necessities of the study at hand. For example, instead of using a motion sensor to track the movements of the arm of a participant to allow the interaction with objects, the derived state could use a different device for the same purpose.

Decision Taking state

Decision Taking is a state that, as the name implies, allows to test decision taking situations. It allows the presentation of a sequence of stimulus, with a break between each stimulus. The presentation of stimulus can be made in two modes: static and dynamic. In the static mode, the participant is only allowed to make a choice using an interaction device (i.e., mouse buttons, keyboard or a gamepad) while the stimulus image remains stationary. In the dynamic mode, there is a pre-defined controlled movement of the camera, in a straight line, and the participant has to make the decision (in the same way as in the static mode) before the camera reaches the end of its path.

Virtual Environments made specifically for this Decision Taking state require an extra configuration file where there are four sections with elements that can be controlled: (1) General; (2) Stimulus; (3) Camera; and (4) Sequence:

1. On the General section it is possible to configure: the velocity to be used by the camera on the dynamic mode; the extra time that participants have to make a decision after the camera reached its destination; since the break duration should be random, it is possible to define the interval of values from which the random duration will be chosen; the background color of the break screen; if an object should be present in the break stimulus (i.e., a cube); the frequency of the data collection which tells the system at what frequency it should save the position, orientation and the choice made in the dynamic mode. If there is intention of giving some auditory feedback for the participant in the choice moment, three sounds can be configured and associated with the system: two

sounds for when the participant makes the selection within or outside the allotted time and a sound for feedback of a choice made;

2. On the Stimulus section it is possible to configure: the total duration of presentation of the stimulus in the dynamic mode, i.e., the total duration that the camera takes from the start point until the end; the duration that the static stimulus is presented; the duration of the extra time allowed, after the stimulus duration finishes, for the participant to make a decision; and the start and end point of the camera within the stimulus;
3. On the Camera section is it possible to define: the height of the camera; an initial angle for the camera instead of the line of sight being parallel to the floor by default; the vertical field of view; and the aspect ratio of the image presented. These last two elements are important to make sure that the representation of objects is in the adequate size and proportions depending of the distance of the participant to the viewing device, e.g., the projection screen;
4. It is on the Sequence section that the mode to use is defined (i.e., static or dynamic). For this type of VEs small sections of a building are usually used. As such, as a convention in the creation moment, it was defined that each one of these sections should have a dummy object that would represent the start position for the camera for that section. This dummy object should have a recognizable name format since those names should be placed in the sequence configuration file in the order that they should appear. Also, those are the names that will appear in the log files.

Because of the nature of the type of study, this mode of the ErgoVR system will export data in a different format than other modes. An extra file with information is exported, which is specific to the choices made for each section present in the sequence defined. As such, the data exported per stimulus is the name of the stimulus (i.e., name of the dummy object of the section of the building or the break stimulus), followed by the choice made, the absolute duration that reflects the time that participants took to make the choice since the beginning of the presentation of the stimulus. At the end of each entry for each stimulus the position and orientation of the camera in the moment of the choice are also present.

For later confirmation of the configuration at which the VE was tested, a report of the configuration used for that participant is also presented in the beginning of the log file.

Decision Taking Simulation state

The main difference between the Decision Taking Simulation mode and the Decision Taking is that that the navigation can be controlled by the participant, by using a navigational interface (e.g., a joystick).

In the configuration file the differences are in the Sequence section which now allows to also have a *navigation* mode besides the static and dynamic and also the respective sequence of stimulus line. The remaining functionality is common with the Decision Taking state.

Walk-in-Place Simulation state

The Walk-in-Place Simulation was built over the Normal Simulation state and as such as most of its functionality. The main difference for this state is the added support for the Walk-in-Place navigational interface. This interface was developed specifically for the study described in Chapter III - Navigational Interfaces. As such, details on the Walk-in-Place navigational interface are also present in that chapter.

Another difference is the exchange of the device of interaction with objects in the environment. For the Walk-in-Place Simulation, a Genius Ring Mouse is used instead of the motion sensor for controlling the onscreen cursor. More details on how the Ring Mouse is used are also explained in detail on Chapter III - Navigational Interfaces.

b) Custom subsystems

In this topic, the ErgoVR subsystems that were developed in its entirety by the author of this document, will be detailed. The subsystems are: Configuration System, Log System and Event System.

Configuration System

The ErgoVR system has certain features that can be configured in an XML file (eXtensible Markup Language). The configuration file allows the researcher to configure the ErgoVR system in a simple manner without the need of recompilation of the entire system.

At this moment, it is possible to configure the system according to the following categories: (1) general; (2) input devices; (3) output devices; and (4) state specific features.

Regarding point 1, the general features that can be configured are:

- Define the state that should initialize;
- Define a default height for the virtual representation of the participant, in meters;
- Define a default translation and rotation speed that will be used by all the states;
- Define a default start position;
- Define a default lightning mode, where it can be chosen to use the default lightning mode defined in the VE or the creation of one or four default directional lights.

The input devices (point 2) can be configured as follows:

- It is possible to enable or disable support for the 3D mouse;
- Regarding the support for the Nintendo® Wii Balance Board, it is possible to:
    - » Enable or disable support for the Balance Board;
    - » Define a dead-zone square where small movements of the participant will be ignored;
    - » Define the rotation and translation sensitivity, i.e., define how the system should react faster or slower to the movement in the Balance Board.

- Regarding the Joystick support, it is possible to configure a dead-zone where movement will be ignored and also the sensitivity of the device;
- Regarding the motion sensors (i.e., the motion sensor for tracking the head and hand movements) it is possible to define:
  - The number of connected devices and which port of the computer they are connected;
  - The minimum variation threshold from which it will be considered new data, i.e., a raw simple data filter in order to ignore extremely small data variations;
  - For the hand sensor it is possible to define the area, from the transmitter, that will be considered as a working area to accept input to be used for the interaction with objects in the VE. It is also possible to define the minimum forward movement distance that the participant should make to simulate the pressing of a button for example.

It is possible to configure the output devices (point 3) in the following manner:

- Turn the sound on or off;
- Regarding the window of the simulation it is possible to define:
  - The width and height of the application window as well as its relative location in the screen;
  - If the simulation should be presented in a secondary monitor if available;
  - If the simulation should be presented in full screen;
  - The FSAA (Full Screen Anti-Aliasing) value as well as the VSync graphical option.
- Regarding the presentation of stereoscopic output it is possible to:
  - Turn on or off stereoscopic support;
  - Define how should be the split in the screen of the images from both eyes: vertical or horizontal;
  - Define the visualization distance to the screen for the correct calculation of the Field of View of the image presented, giving a correct representation of the objects of the VE. This feature is most useful when using the projection.
- Regarding rendering properties it is possible to define the near and far clip plane distances. These allow to define the distance interval from the camera that objects will be rendered;
- Regarding the Sensics® ZSight Head-Mounted Display, it is possible to define if the ErgoVR system should consider to use its internal motion sensor or not, the update rate at which data from the sensor will be processed and also the Field of View that it is configured on the ZSight (60° or 70°).

And finally, it is possible to configure the following state specific features (point 4):

- The path for the scene to load for each state;
- The default translation and rotation speed for each state.

Log System

The Log System is one of the most important subsystem of the ErgoVR system. It is responsible for saving automatically what happens inside the simulation. In Figure 6, it is possible to see how a log file created by this subsystem is structured.

A log file is comprised of two sections: header and a sequence of log entries. The header section has the following information: an identification number, the log file name, the scene name that was being simulated at the time and an optional area that can be used to write extra information that could be necessary for certain states. The sequence of log entries section is composed of structures of the type *LogEntry*.

A *LogEntry* has two major areas of information as it is possible to observe in Figure 6: one that is static (i.e., appears in every *LogEntry*) and another that is complementary (i.e., it can be added to a *LogEntry* when necessary).

The static information blocks are: (1) *Time*; (2) *Position*; (3) *Head Orientation*; and (4) *Body Orientation*. The *Time* represents the instant of time when that specific *LogEntry* was saved. The *Position* is a tridimensional vector that represents the position of the participant in the VE at the moment that the entry was saved. The *Head Orientation* gives the head orientation (more specifically, the camera's orientation) of the participant at the same moment in time. The *Body Orientation* represents the orientation that the body had at that time. Both orientation values are saved as quaternions, which are mathematical structures to represent tridimensional rotations, invented by Sir William Rowan Hamilton (1844). A quaternion can be represented by a tridimensional vector and a scalar. This property of having four real numbers allows to save space in the log file when compared to save a rotation matrices, which requires nine real numbers. Quaternions are most used in computer graphics after they were formally introduced to this community by Shoemake (1985).

The complementary information blocks are: (1) *Trigger Pressed*; and (2) *Extra information*. The *Trigger Pressed* information block will present the name of the trigger that was activated at that instant of time, if any. The Extra Information block can have any extra information that might be required by a specific state (e.g., the object that the participant was looking at that the time).

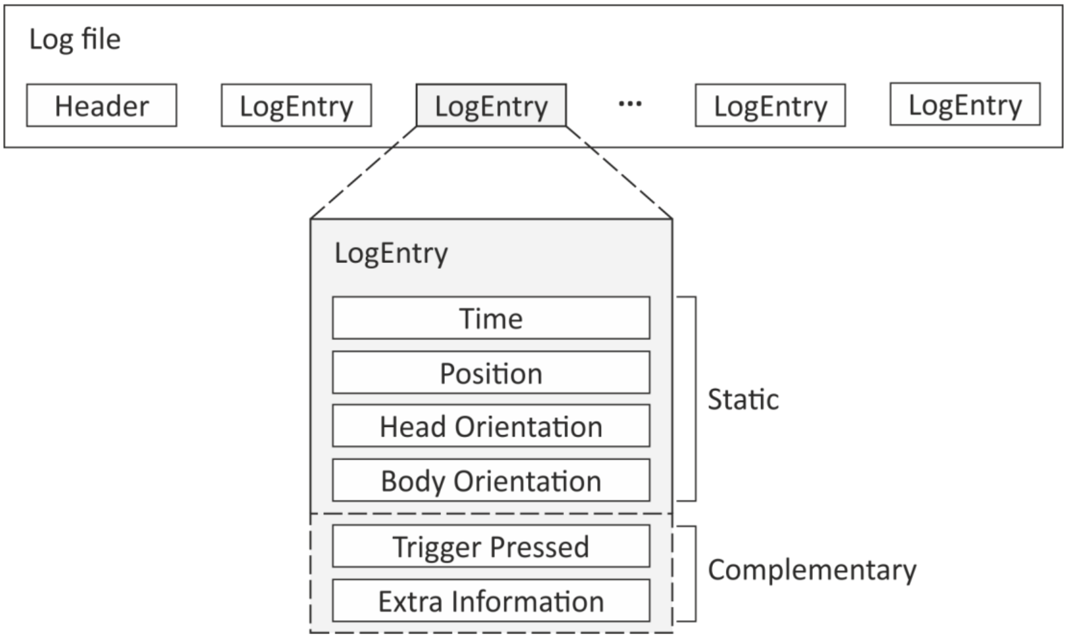


Figure 6 - Log file and LogEntry structure

By default, the Log System saves log entries at a frequency of 60 times per second. This value is configurable if desired. This sequence of log entries is enough to gather different types of information that can be extrapolated by post-processing the saved data. For example, the path taken by a participant is taken from all the *Position*s present in all the entries available. All the possible data that is exported and extrapolated from the log files is explained in more detail in topic 2.3.4 - LogViewer.

To save space in the final log files, the Log System uses a differential data format to save each *LogEntry* structure. This means that only the information that changes is recorded for each entry. For example, if the participant is stationary, the *Position* information is only recorded for when the participant stopped and as soon movement resumes. Depending on the type of study and movement required from the participant in the VE, this differential format can save from a few Kilobytes of information (for VEs where the participant is required to move very often) to several Megabytes of information (for VEs where the participant is not required to move often).

Event System

Causality can be defined as the relationship between *causes* and *effects*. In the classical physics standpoint, a *cause* always precedes its *effect*. For example, in Newton’s second law of motion (Newton, 1934), a force acting on a body can be a representation of the *cause* and the acceleration that follows would be the *effect*. In a VE, most of the interactions that are possible to do are based on causality. For example, it is possible to when a person interacts with an old door (cause), the door would open and a low ranging sound would play (effects).

The causality induced type of interaction is the main reason for the creation of this Event System. Its main purpose is to create a medium that will allow a researcher to have a wide range of possibilities in terms of the definition of *causes* and corresponding *effects* in a structured and declarative form which would make it easy to learn and use.

Intrinsically, two types of elements were created to be used in the VEs: *triggers* and *actions*. A *trigger* is an element that represents the *causes* in a VE and it is an element that acts as a detector of contact with the participant's virtual representation, activating at that moment a corresponding set of *actions*, i.e., when the participant enters in contact with a *trigger* in the VE, a set of actions that are associated with that *trigger* will be activated. The *action* element represents an actionable *effect* in the VE and can be of several types, which will be detailed further in the document. An *action* occurs as an actionable response (an effect) of a contact with a *trigger* (the cause) which is always represented by some form of change in the VE or as a feedback for the participant (e.g., a sound playing).

For the remainder of the document, the elements in the Event system are called by what they do rather than what they represent, i.e., *triggers* are the causes and *actions* are the effects.

A trigger, by defined convention, can be any type of object inside the VE and as such, there are different uses for a trigger. For example, a trigger can be placed in an area to detect if a participant passed through that specific part of the environment. In this case, a trigger works much like a motion sensor (e.g., a proximity sensor). However, it can also be used in other situations. For instance, there might be the need to detect if a participant tried to interact with a specific object in the VE in order to provide with some sort of feedback (e.g., changing the color of a button when the participant interacts with it). That object can be a trigger and it is considered a contact trigger. This property of triggers can be used, for example, to detect collisions with specific objects.

A trigger has two states: a *disabled* and an *active* state. A trigger can be initialized in the *disabled* state and later being changed into an *active* state. As such, and assuming that such trigger is in its *active* state, it can be activated in four situations:

- The interaction device was used in the simulation (e.g., a cursor is over a trigger object and a button is pressed over it);
- A keyboard key was pressed to activate a pre-defined trigger;
- There was an active contact of the participant's virtual body and a trigger in the VE;
- An initial time for automatic trigger activation has passed since the beginning of the simulation.

An *action* is something that can be activated in response to a specific event (i.e., the activation of a trigger). There are several types of different actions that can be used which are detailed in the *Action features* topic below. For example, if someone has placed a trigger on a door knob, one resulting action might be the activation of an animation that would open the door. Another example would be if someone placed a trigger at the door of a room, a possible action might be to turn the lights on when the participant enters the room.

Triggers and *actions* can be defined in several different ways and have different features which can be configured depending on the intended purpose and the situation where they will be placed. Details of its features are given in the following subtopics.

Trigger *features*

As mentioned before, a trigger can be represented by any object in the VE and all triggers are contact triggers. This means that, by default, as soon as the participant enters in contact with the trigger, the associated actions will be activated. As such, this particularity of the system must be taken into consideration in all use cases.

Each trigger, at this time, has the following main properties and associated features, which can be configured:

- *Associated Object's Name* – Since every object in the VE can be a trigger, it is necessary to create the association between the visual object and the trigger being created. This is done by associating the name of the object;
- *List of Actions* – Sequence of actions that are associated with the trigger, i.e., the actions that will be activated when the participant enters in contact with the trigger;
- *Initial Status* – Since triggers can be activated through an action (i.e., activated by the activation of another trigger), this property allows to set the initial status of a trigger as turned off at the start of the simulation;
- *Initial Delay* – It is possible to create a trigger that only activates after a specified amount of time. If a participant enters in contact with the trigger before this time has passed since the start of the simulation, no contact is recorded and also there is no activation of the associated actions;
- *Activate Actions After* – It is possible to automatically activate the associated actions of a trigger after a specified amount of time has passed since the start of the simulation. In this case, the trigger is active but it only activates the associated actions after the amount of time, defined in this property, has passed since the beginning of the simulation. This is a numerical property that receives integers that represent the time in seconds;
- *Activable Multiple Times* – This allows to define if a specific trigger can be activated more than once. For instance, it might be desirable that a certain trigger can only be activated once (e.g., to detect the first pass through a certain area);
- *Associated Key* – A trigger can also be manually activate by a key press on the keyboard. This property allows to define which key will activate the trigger;
- *Visible* – Since a trigger is basically an object in the VE, this property allows to hide or show that trigger. By default, triggers are invisible in the VE.

Action features

An action can be represented by both visual and non-visual objects in the VE. For example, a non-visual object would be the location where a sound will be transmitted. A visual object might be a screen or board in a VE that when a specific trigger is activated, presents different information.

An *Action* has the following main properties and associated features:

- *Associated Object Name* – Since some of the actions can be associated with visual objects, this is required to create the association;
- *Target* - In broad terms, this represents the resource name (or path) that is specific for the action's type (e.g., for a sound it would represent the path for the sound file);
- *Max Duration* – This allows to set a value, in seconds, for how long the action should be active;
- *Initial Delay* – This allows an action to only start a certain amount of time (in seconds) after the trigger's activation;
- *Activation Mode* – This allows to set the activation mode of an action. For example, it is possible to stop an ongoing action or start a new one;
- *Loop* – Most actions have an associated duration. This allows to repeat the action if necessary;
- *Auto Start* – This enables an action to start automatically in the beginning of the simulation, instead of waiting for a trigger activation.

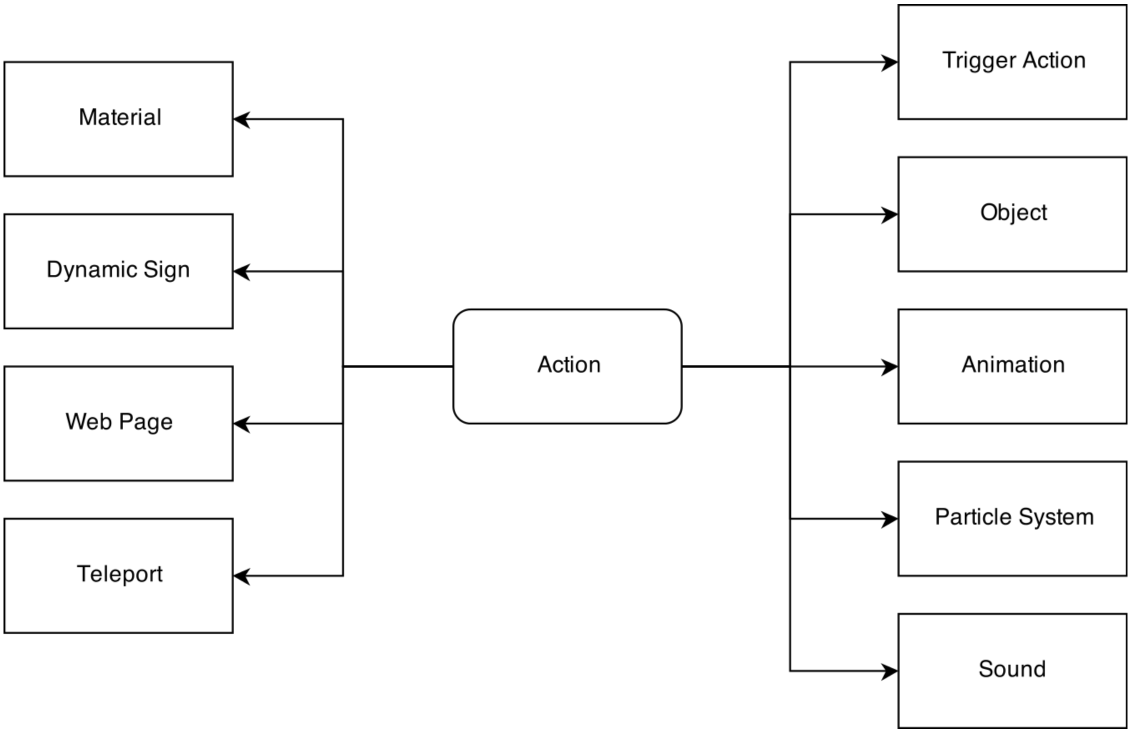


Figure 7 - The different types of Action available in the Events system

Each *Action* can be categorized into different types (see Figure 7) according to their purpose:

- *Trigger Action* – This action allows to activate a disabled trigger. This is useful to detect if a participant went or interacted with the VE after a specific action occurred;
- *Object* – This action allows to show or hide a specific object. It is also possible to control the physical properties attached to this object;
- *Animation* – This action activates a specific animation that is associated with an object;
- *Particle System* – This action activates a particle system. A particle system can be used to present, for example, a fire or some smoke in the VE;
- *Sound* – This action starts playing (or pauses) a sound in the VE;
- *Material* – This action allows to change the material used in an object. The material must exist already;
- *Dynamic Sign* – This is a special action that creates the blinking effect on a dynamic sign. It is possible to define the interval between the on and off state;
- *Web Page* – This allows loading a web page as a texture of an object. It can be used in any object but the main use might be rectangular shapes for defining some sort of interactive display;
- *Teleport* – This action allows to move the avatar from one location of the VE to another instantly. The source and destination locations must be existing objects in the environment (they can be dummy objects) and defined appropriately in the trigger definition;
- *Action Container* – This special type of action is a container for a set of actions that are related to a specific object. For example, an object can have several actions associated with it. This container allows to access each animation independently as it were a single action (e.g., having different animations where each animation can be activated by a different key press). Within the *Action Container* the actions are represented by an integer identifier. The remaining properties are those of normal actions. The *Action Container* is associated to a specific object and as such, all its inner actions are associated to that same object.

Although some of these actions can be fulfilled with only the common elements between all the types of *Action* available, there are some actions that have specific properties which will be briefly described below.

Regarding the ***Object Action*** the following specific properties are available:

- *Start Hidden* – For certain situations, it might be appropriated to have a hidden object that should appear after a trigger is pressed. This Boolean[12] property allows to set the initial visibility of the object;

---

[12] A Boolean property can only have two possible values: *true* or *false*.

- *Physics* – This Boolean property allows to define if the physical properties of an object should be active or not, even in cases that the object is hidden. This can be useful to limit the movements of the participant in certain areas of the VE;
- *Invisible* – This Boolean property hides the object and also removes the physical properties of it at the same time.

Regarding the ***Sound Action*** the following specific properties are available:

- *Ambient* – This Boolean property allows to define if the sound should be considered an ambient sound (i.e., constant sound that accompanies the participant throughout the VE) or a normal positional sound (i.e., a sound that has a specific point of origin in the VE);
- *Reference Distance* – For positional sounds, the reference distance property allows to set at which distance the sound will start fading in volume;
- *Maximum Distance* – This property will set at which distance the sound will stop being heard by the participant;
- *Gain* – This property allows to define the volume gain that should be applied to the original recorded sound.

Regarding the ***Dynamic Sign Action*** the following specific properties are available:

- *Interval* – This property defines the interval, in milliseconds, at which the sign will change from the "on" to the "off" state, i.e., the frequency at which the sign will blink;
- *Self-Illumination* – This represents the RGB (Red, Green, Blue) color to be used in the "on" state of the dynamic sign.

Regarding the ***Web Page Action*** the following specific properties are available:

- *Texture Width and Height* – These properties represent the width and height, in pixels, of the image that will be rendered with the web page content. This later will be applied as a texture to the associated object;
- *Transparent* – This property allows to define if the rendered image of the web page should support transparency, i.e., instead of having an opaque background color, it would be transparent. This would allow to present translucent content over an object (e.g., displaying information on glass);
- *Keys Functions* – In the case of web pages, it is possible to assign a key to activate a certain function on the web page, i.e., to execute a certain web page specific action by pressing a key. This property is a container that has the pair information of the key and the associated function to activate when pressing it.

Practical example

To see how the features of triggers and actions work together, it is easier by observing a simple example where some of those feature can be used. The objective for this particular case is knowing how much time the participant takes inside a room and also how much time was necessary to follow an instruction that requires the press of a button.

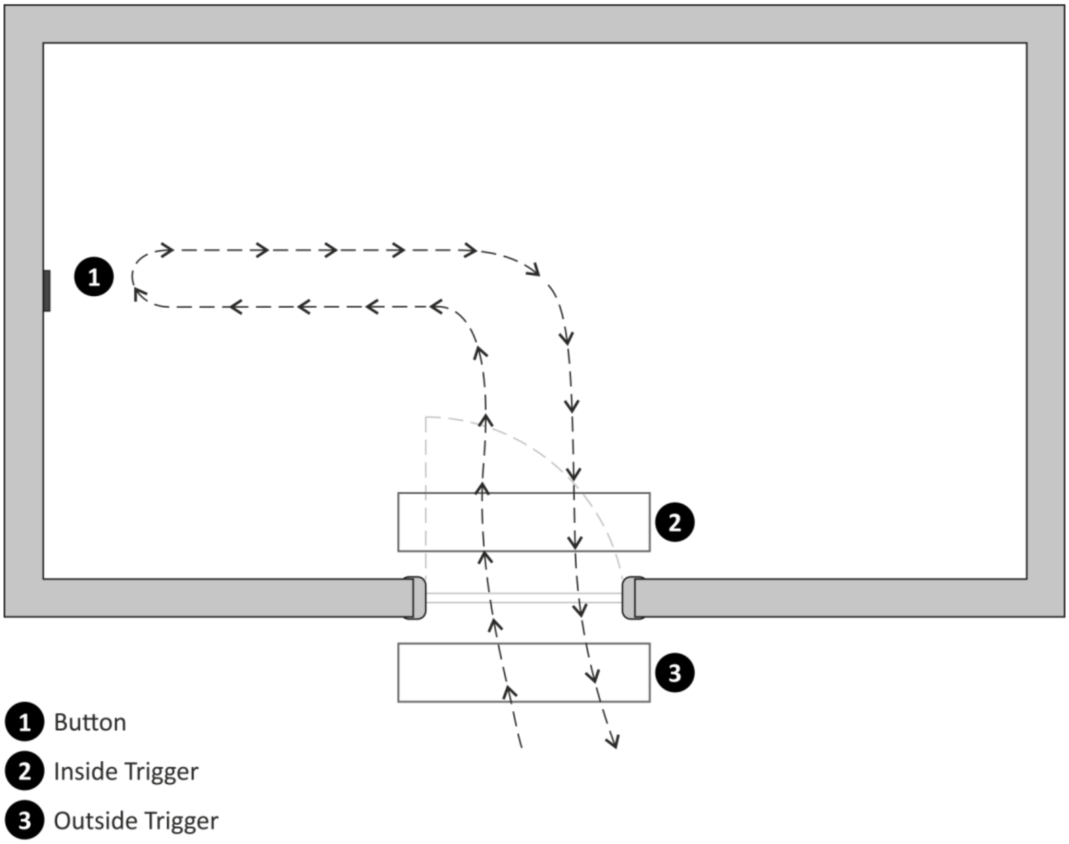


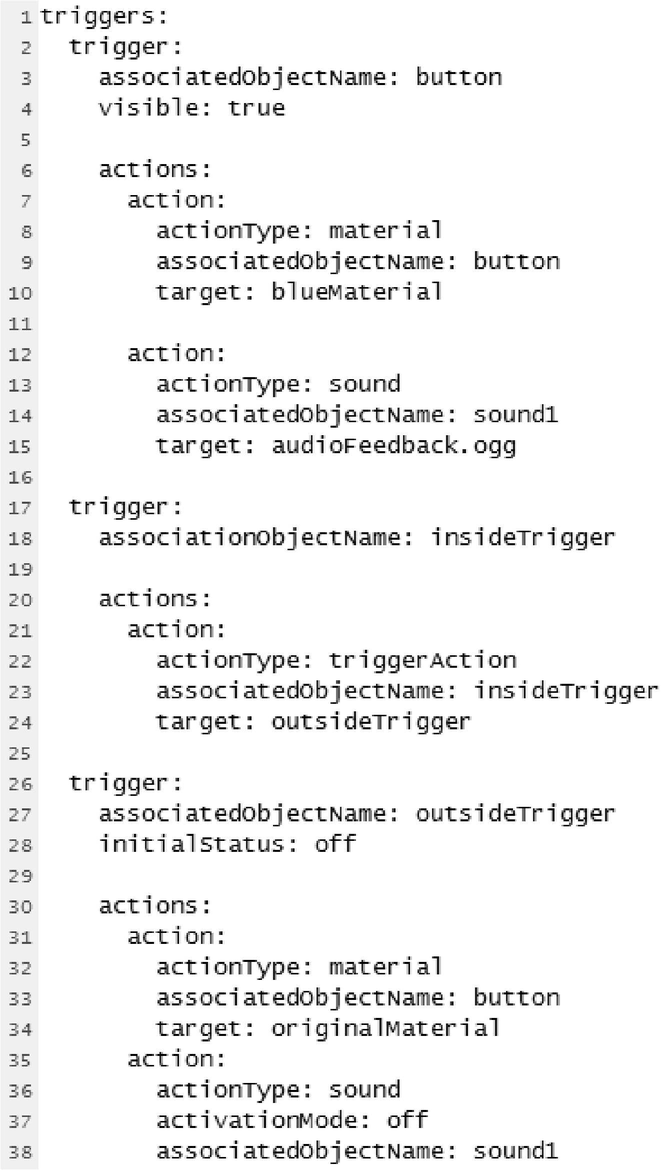
Figure 8 - Practical example room with some triggers and a button

In Figure 8, it is possible to see a top-view image of a simple room. There is an instruction posted on a wall and there is a button that should be pressed (as stated by the instruction). The button itself is a trigger which when activated by the participant, changes its color as well as play a sound as a form of feedback of the interaction. There are two other triggers at the entrance of the room. The triggers will act as start and end point of the duration that the participant was inside the room. The trigger that is inside the room (called *insideTrigger*) will be active from the beginning and will be the starting point and the one outside (called *outsideTrigger*) will be disabled and act as the end point. The outside trigger will be activated by the inside trigger and when the participant exits the room it will reset the state of the scene (by activating the inside trigger and changing the button color to the original one).

As mentioned in a previous section (*2.3.2 - Creation of Virtual Environments*), it is required, at design time to define the association between the *triggers* and *actions* that will make part of the

VE. That association is made in a textual format and it must be added as extra information to the *Events* dummy object in the VE.

The textual format created is based in XML (Extensible Markup Language) which allows to define a set of rules, in a human-readable form. The information in this type of documents are presented in a structured hierarchy and there is an attribute-value association. For the sake of simplicity, a simplified version of the resulting XML is going to be presented, where the hierarchy is represented by indentation and the attributes are separated from their corresponding values by a colon.



```
triggers:
  trigger:
    associatedObjectName: button
    visible: true

    actions:
      action:
        actionType: material
        associatedObjectName: button
        target: blueMaterial

      action:
        actionType: sound
        associatedObjectName: sound1
        target: audioFeedback.ogg

  trigger:
    associationObjectName: insideTrigger

    actions:
      action:
        actionType: triggerAction
        associatedObjectName: insideTrigger
        target: outsideTrigger

  trigger:
    associatedObjectName: outsideTrigger
    initialStatus: off

    actions:
      action:
        actionType: material
        associatedObjectName: button
        target: originalMaterial
      action:
        actionType: sound
        activationMode: off
        associatedObjectName: sound1
```

Figure 9 - Definition of the events for the simple example

As it is possible to see in Figure 9 we have an element called triggers which will contain all the triggers involved in the VE. In the example, it is possible to see three triggers, i.e., the button, the *insideTrigger* and the *outsideTrigger* as it can be seen in the *associatedObjectName* attributes inside each trigger. Since all triggers are hidden by default, it is necessary to set the button as visible (line 4). As mentioned earlier, the button will have two actions associated with it, the change of a material and a sound will be played. This is represented by the two actions that are within the button trigger definition (starting on line 6). Looking at the first action definition (lines 7 to 10), it is possible to see that it was defined the type of action to be used (material), give the *associatedObjectName* which will be the object that will be affected by the material change (button), and finally by defining the target which must be a pre-existing material (for this particular example, a *blueMaterial* was already defined which only sets the color to blue). For the second action of the button (lines 12 to 15), it is defined the type of action to be as sound, the *associatedObjectName* of the location of where that sound will be played (this is usually represented by a dummy object in the VE). This is necessary since the ErgoVR system has a positional sound system and as such, if sound locations are used in the VE, the participant will have a perception of the source location of the sound. Finally, the sound file path is given as a target to the system (line 15). Next, it is possible to see the definition of the *insideTrigger* (lines 17 to 24). This trigger has a single action, which is the activation of the *outsideTrigger* as it can be seen by the target (line 24). Lastly, when the participant activates the *outsideTrigger*, it is desirable to “reset” the scene to the initial state, in case the participant decides to enter the room again. Also, we want that the trigger will be disabled at the start. As such, the definition for the *outsideTrigger* (lines 26 to 38) has the *initialStatus* set to off and it has two associated actions for the “reset”. The first action is to change the material of the button to the original color (represented by a pre-existing material called *originalMaterial*). The second action is to turn off the sound. In this case, it will not be required to define a target. It will be required however to set the *activationMode* to off (line 37).

With this simple events definition assigned in the creation of the VE, the Event system is able to process the information automatically while loading the VE and set the triggers and actions as defined. During the simulation, when the participant interacts with the triggers (being it the ones on the floor as with the button), the Events system will activate the actions appropriately.

c) Currently compatible hardware

Although the ErgoVR system was developed to be open to different types of hardware, the hardware components that were tested to be compatible with the system will be briefly enumerated according to their function within the ErgoVR system: **interaction**, **visualization** and **processing** components.

Interaction components are responsible for the actions performed by the users in the virtual environment such as **navigation**, **motion detection**, **manipulation**, **auditory** and **visual** devices.

At the moment, the ErgoVR system works with ***navigation** devices* such as the keyboard and mouse, joysticks, a 3D mouse (3DConnexion SpaceNavigator with 6DOF), the Nintendo® Wii Balance Board and a Walk-in-Place interface. As ***motion detection** devices*, ErgoVR works with three magnetic motion sensors (Ascension-Tech® Flock of Birds), two inertial Intersense® InertiaCube3 sensors and ten inertial motion sensors (XSens® XBus Kit with 10 MTx sensors) to capture the motion of the participant. For ***manipulation** devices*, ErgoVR works with a VR data glove that captures the flexion of the fingers (5DT Data Glove 5 Ultra). For ***auditory** devices*, ErgoVR can reproduce sound through a set of headphones or through a 5.1 surround system. Although the visualization devices are part of the interaction devices and because of its importance, they will be mentioned separately. The ErgoVR system is also compatible with the Sony® Buzz! Buzzer USB controller which has one big button and four small colored ones.

Visualization components are responsible to present the VEs to a participant. ErgoVR can reproduce those VEs through a 3D Projector (Lightspeed DepthQ 3D projector), a 3D monitor (Samsung 2233RZ), common computer monitors and through stereoscopic and non-stereoscopic Head-Mounted Displays (HMD). The ErgoVR system was tested with the non-stereoscopic HMD from Sony®, model PLM-S700E. Also, several Sensics HMDs were tested, more specifically the piSight 145-41b, xSight 6123 and the zSight models.

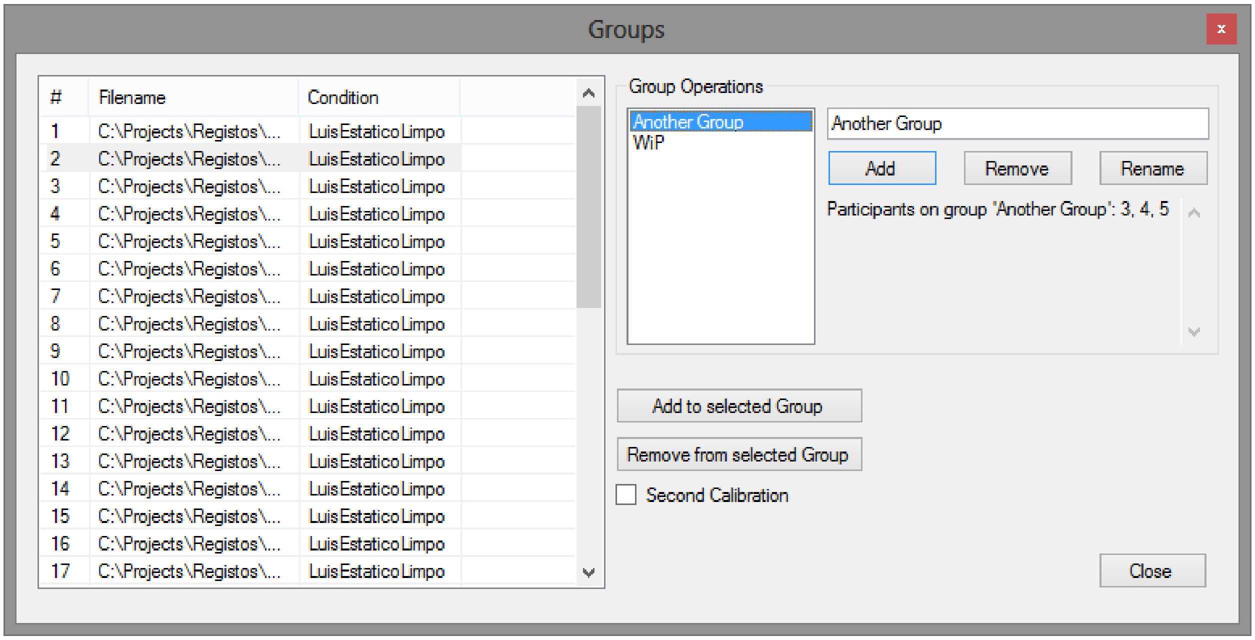
Processing components are the ones that perform the calculations required to display and process the information that is transmitted from the different input devices. At the moment, the ErgoVR system is comprised of two main computers with NVIDIA® Quadro® graphics cards (FX4600 and FX5800) so the VEs can be processed and presented to the users. At the same time, those computers are equipped with Intel® i7 processors that are able to process all the required data in real time.

2.3.4 LogViewer

The *LogViewer* application is used to allow the researcher to analyze and export the data from the simulations made with ErgoVR.

The *LogViewer* works by allowing the researcher to create a study's project file, which will contain a link to the data folder (the location for the ErgoVR's recorded files) for that particular study, as well as a link for the output folder where the application will export all the data. It will also have extra information required for the different work modes of the application (e.g., environment top view image, groups created).

Usually, a researcher needs to separate the data into different experimental groups (e.g., per experimental condition). The *LogViewer* allows the researcher to create these groups of participants so that the data can be exported accordingly. If no groups are defined, the data is exported as it was part of a single group. In Figure 10 it is possible to see the Group window.



#	Filename	Condition
1	C:\Projects\Registos\...	LuisEstaticoLimpo
2	C:\Projects\Registos\...	LuisEstaticoLimpo
3	C:\Projects\Registos\...	LuisEstaticoLimpo
4	C:\Projects\Registos\...	LuisEstaticoLimpo
5	C:\Projects\Registos\...	LuisEstaticoLimpo
6	C:\Projects\Registos\...	LuisEstaticoLimpo
7	C:\Projects\Registos\...	LuisEstaticoLimpo
8	C:\Projects\Registos\...	LuisEstaticoLimpo
9	C:\Projects\Registos\...	LuisEstaticoLimpo
10	C:\Projects\Registos\...	LuisEstaticoLimpo
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12	C:\Projects\Registos\...	LuisEstaticoLimpo
13	C:\Projects\Registos\...	LuisEstaticoLimpo
14	C:\Projects\Registos\...	LuisEstaticoLimpo
15	C:\Projects\Registos\...	LuisEstaticoLimpo
16	C:\Projects\Registos\...	LuisEstaticoLimpo
17	C:\Projects\Registos\...	LuisEstaticoLimpo

Another Group

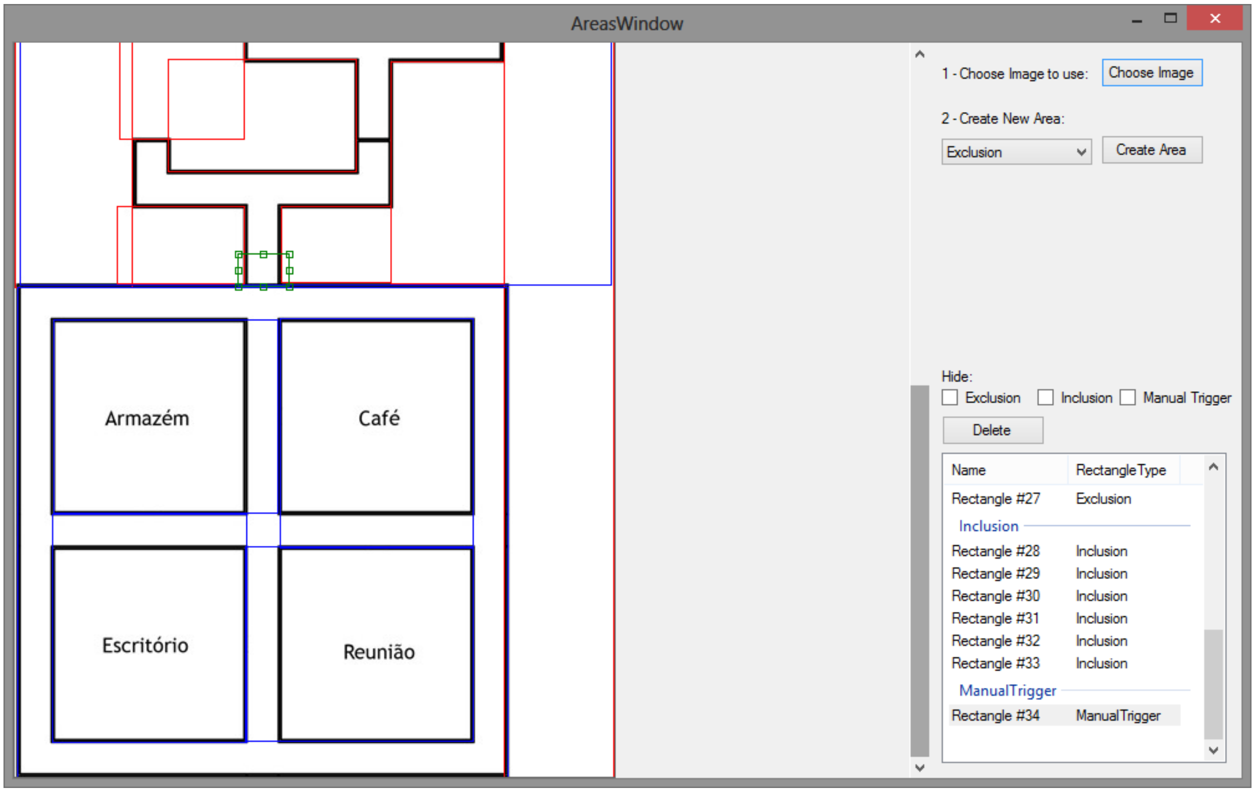
Participants on group 'Another Group': 3, 4, 5

☐ Second Calibration

Figure 10 - LogViewer's Group window with an example

On this window, it is possible to add, remove or update groups and also associate participants to each group. On the right side of the image it is possible to see that the "Another Group" group is selected and it is presented a sequence of the participant's numbers that belong to that group. The list of participants that is presented in this window is gathered from the folder that was given as the data folder when creating the project and as such, shows a list of all the participants.

Another feature of the *LogViewer* is that it is possible to define different *areas* of an environment. The main purpose of this feature is to allow the researcher to analyze the environment into different parts (e.g., an environment that has distinctive types of task in different areas). It also allows to create two types of areas (i.e., inclusion and exclusion areas) which specifies that information from those areas are exported or not. If the objective of the researcher is only to physically separate two parts of the environment and get all the information for each one, the researcher can create a *manual trigger*. Where the inclusion and exclusion areas will only export the information regarding those areas and not from the complete simulation, this *manual trigger* element only creates a separation point to present the complete information of the simulation. The data exported will be presented for the complete simulation and also taking into account the separations that might exist, created by a *manual trigger*. In Figure 11, it is possible to see an image of the Areas Window. The first step is to load a top view image that is representative of the environment and after that new areas or manual triggers can be created. On the right side of the window it is possible to see a complete list of the elements already added. An area is defined as a rectangular shape and can be resized as the researcher wants. The selected area shows the resize points that are represented by squares, as it can be seen in the green rectangle.



1 - Choose Image to use:

2 - Create New Area: Exclusion

Hide:
☐ Exclusion ☐ Inclusion ☐ Manual Trigger

Name	RectangleType
Rectangle #27	Exclusion
Inclusion	
Rectangle #28	Inclusion
Rectangle #29	Inclusion
Rectangle #30	Inclusion
Rectangle #31	Inclusion
Rectangle #32	Inclusion
Rectangle #33	Inclusion
ManualTrigger	
Rectangle #34	ManualTrigger

Figure 11 - LogViewer's Areas window with an example

With the concept of groups and areas that was described, the *LogViewer* allows a researcher to view and export both qualitative and quantitative data. It can take into account: 1) an individual participant's data; 2) a selection of some participants; 3) pre-defined groups of participants; and 4) the complete simulation or certain selected areas of the VE.

The qualitative data allows the researcher to observe the path that the participant took in a top view of the environment. The *LogViewer* also allows to overlap several paths, with different colors, in case a group of participants is selected. In Figure 12 it is possible to see an example of an exported image of the top path, with a participant's path. In the simple example presented, participants had to find the Locker-room (*Locker room* in the image), where they had signs to direct them. Although a simple example, it is possible to see that the participant moved very close to the walls, instead of being more in the center of the corridors. Although a subjective analysis, this could be an indication that the participant was having some difficulties controlling the navigation interface. However, it is clear that the participant chose the more direct path to the destination.

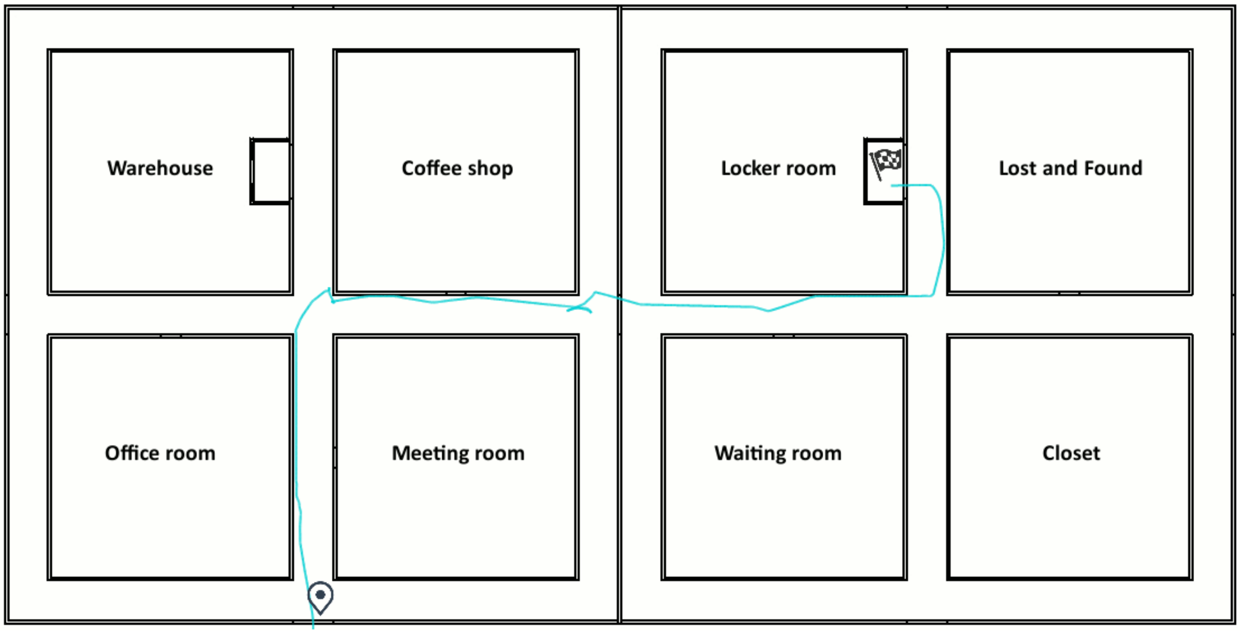


Figure 12 - Example of an exported image of a participant's path

This qualitative mode of viewing the data is useful for reviewing more general aspects of the users' behavior during the simulation such as the most visited areas of the VE, or if the user had some problem with the navigation, navigation and space exploration patterns, hesitations, among others. Another form of qualitative data that is available is in the form of space exploration matrices which is detailed in the subtopic *2.3.4a) Space Exploration Matrices.*

Regarding the quantitative data, the *LogViewer* application allows the visualization of the simulation's recorded data and extrapolates the following additional data, which can be exported: 1) Distance travelled; 2) Duration of the simulation; 3) Pauses; 4) Average Speed; 5) Triggers activated; 6) Observed objects; 7) Object collisions; 8) Choice of direction; and 9) Space exploration matrices.

In terms of Distance travelled, Duration of the simulation and Average speed (points 1, 2 and 4 respectively), the *LogViewer* application exports this information globally and per each area that was defined. The distance travelled is calculated through the position of the user at the environment (as recorded by the *LogSystem*), from the start of the simulation until the required point (per area or per activation of a trigger). The duration is simply gathered by the subtracting the timestamp that is recorded in the current point in the VE and the initial starting point. The Average speed is calculated by dividing the distance travelled by the duration until that point (end of simulation or beginning of an area).

Regarding point 3 (Pauses), the number of pauses, as well as a sequence of all the pauses with individual durations are exported. Also, other information regarding the duration of the pauses is exported such as the minimum, maximum, average and standard deviation. The researcher can change the value of the pause (in milliseconds) and the *LogViewer* will make the calculations accordingly by analyzing the locations where the participant remained stationary for at least the amount of time defined in the interface.

Regarding the triggers that were activated (point 5), information regarding which triggers were activated is exported and in those cases, the distance already travelled and the duration in the simulation since the beginning until the first activation of that trigger are also exported. A complete ordered sequence of the activated triggers are exported.

The observed objects (point 6) are objects that were defined at design as observable objects and, at the moment, the center of the field of view entered in direct contact with them. A sequence of the objects observed and respective duration of observation are exported. This feature is present considering a future integration of an eye-tracker system where it would allow the researcher to have more concrete data than only the center of the field of view (which might not necessarily mean that the person was looking at the object at that time). Also regarding objects is point 7 where it is possible to analyze the collisions with certain objects (defined at the VE design time). A list containing the sequence of the objects that the participant collided with, with the instant of time the collision happened since the start of the simulation and a total counter of collisions with a particular object is also exported.

The choice of direction (point 8) is a feature mostly used for wayfinding studies where data is exported in a way that facilitates the analysis of the choice of direction the participant took throughout the environment. Space exploration matrices (point 9) are exported in tabular data for posterior analysis in statistical analysis software (e.g., SPSS) as well as presenting an image. More details on space exploration matrices are presented in subtopic *2.3.4a) Space Exploration Matrices.*

a) Space Exploration Matrices[13]

Space exploration matrices are a way to know in which areas of the environment the participant walked on. This can be presented in both visual and numerical forms which will be described in this topic. Space exploration matrices can be created in the *LogViewer*'s Grid window which is presented in Figure 13.

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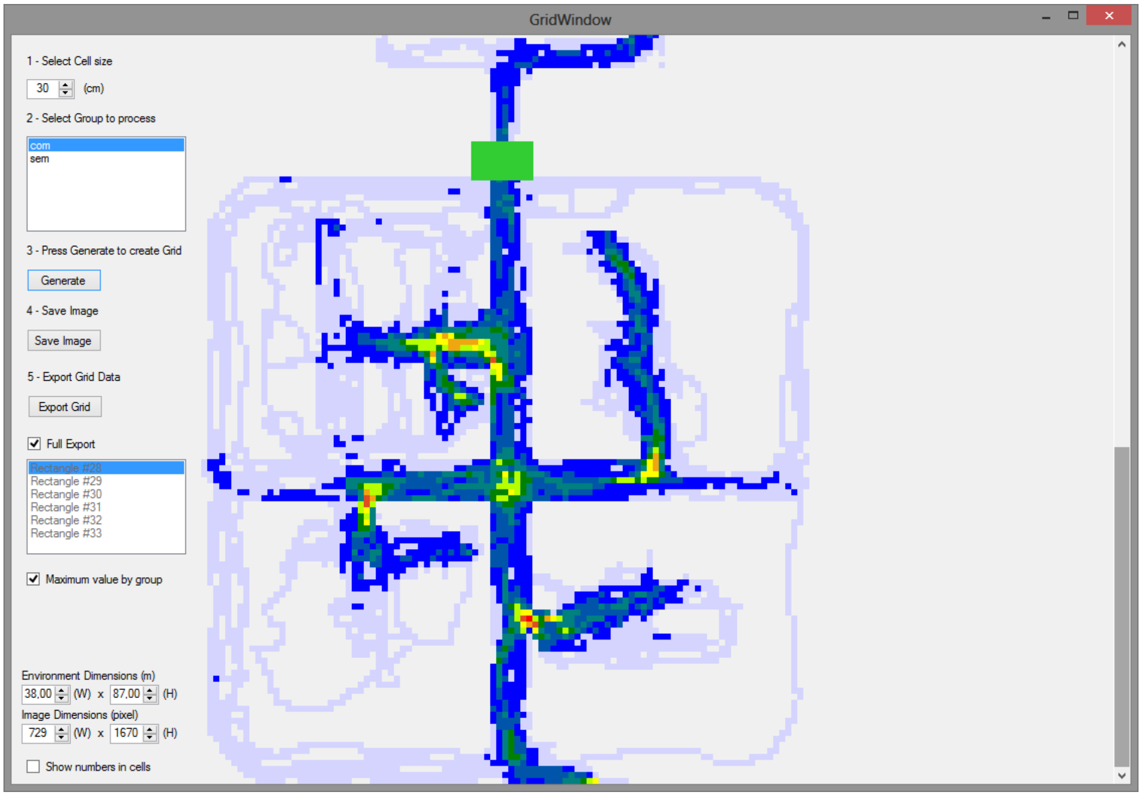
[13] Parts of this topic are from the following paper "Teixeira, L., Duarte, E., Teles, J., Vital, M., Rebelo, F., & Moreira da Silva, F. (2013). Using space exploration matrices to evaluate interaction with Virtual Environments. In F. Rebelo & M. Soares (Eds.), *Advances in Usability Evaluation Part II* (pp. 3–12). Boca Raton, FL: CRC Press/Taylor & Francis, Ltd."



1 - Select Cell size
30 (cm)
2 - Select Group to process
com
sem
3 - Press Generate to create Grid
4 - Save Image
5 - Export Grid Data
☑ Full Export
Rectangle #28
Rectangle #29
Rectangle #30
Rectangle #31
Rectangle #32
Rectangle #33
☑ Maximum value by group
Environment Dimensions (m)
38,00 (W) x 87,00 (H)
Image Dimensions (pixel)
729 (W) x 1670 (H)
☐ Show numbers in cells

Figure 13 - LogViewer's Grid window

The Grid window allows the researcher to select which group (previously defined in the Group window) to present the space exploration matrices. These space exploration matrices of the VE consist in a squared grid (with configurable cell dimensions) where each cell has an associated color and number.

The color of each cell is assigned from a 11 pseudo-color scale (Ware, 2004) to indicate the “warm” zones (warm colors means that the cells were stepped on more) e “cold” zones (colder colors means that the cells were stepped on less). Since that the colors are based on the highest cell frequency level from the complete VE, in case several experimental conditions are intended to be compared, the *LogViewer* allows the researcher to activate an option which will calculate the grids for all the experimental conditions and use the maximum value as a base to the normalization of the presented colors. The visual end result is a heat map image of the locations where participants walked inside the VE. This image can be exported. The green rectangle in Figure 13 represents the rectangle for a *Manual Trigger* that separates two areas of environment which was also shown in Figure 11. The presentation of these *Manual Triggers* is optional.

The number represents the frequency that each cell was stepped on during the simulation. It was defined as a “stepped on cell” the cell that was intersected by the point that represents the middle axis of the “virtual body”, perpendicular to the floor, i.e., the center of the projection of the representation of the participant in the VE. Each time that the “virtual body” enters the cell, the frequency value of that cell increases by one unit. The frequency of that cell only increments whenever the "virtual body" enter within a cell, therefore the moments where the participant is stationary over a cell only counts as one. Since this tool is to be used on groups of participants (usually one for each experimental condition), the frequency value of each cell represents the sum of the frequencies of every individual in that group. This numerical information, depending on the size of the VE and the size of the cell, can be immense. As such, and since there are several areas on the top view of the environment that the participants could never reach (e.g., empty spaces), the *LogViewer* allows to export only the numerical information ignoring all the exclusion areas (defined previously in the Areas window). It can also export a single inclusion area.

A practical example of the use of space exploration matrices was made by a study (Teixeira et al., 2013) that wanted to evaluate human interaction with VEs. For that, the space exploration matrices for five experimental conditions were compared. In that study, and assuming that the most salient warnings (dynamic) would be detected more easily than the static counterparts, it was hypothesized that such differences would be manifested in the spatial exploration of the VE. More dispersion of the participant's position in the VE, resulting in a higher diffusion of the stepped cells (an indicator of greater search, in vaster areas), as well as higher frequencies of "steps" in some of the cells (indicator of hesitation and/or need of a more detailed search in that particular area), were expected in the experimental conditions where the warnings are less salient (static) and the environment is more visually polluted.

In Figure 14 it is possible to visualize the five matrices (from the complete VE), one for each experimental condition, with cell size of 50×50 cm. This size was adopted since it was closer to the 95th percentile for the male shoulders' width (51 cm) (Pheasant & Haslegrave, 2006).

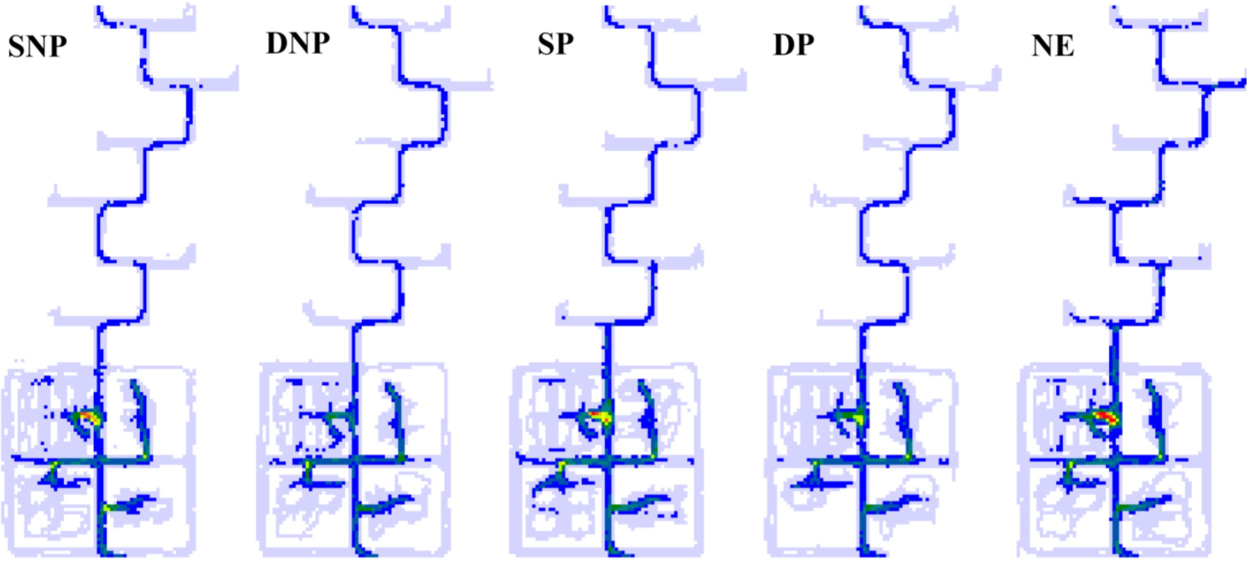


Figure 14 - Space exploration matrices of the VE, per experimental condition

In that study, the “agreement” of the space exploration matrices, for the areas of interest defined, was evaluated through the application of the Concordance Correlation Coefficient (CCC) (Barnhart, Haber, & Song, 2002; Lin, Hedayat, Sinha, & Yang, 2002; Lin, 1989) considering the frequency that the cells were stepped on as the variable of interest.

The findings in that study revealed high values of “agreement”, which allowed to conclude that there was not a significant influence of the experimental condition on the space exploration of the VE.

2.4 Evaluation of ErgoVR

The ErgoVR system was used as a tool in several studies, namely in the fields Cognitive Ergonomics and Physical Ergonomics. In this topic, two case studies, from these fields, that used the ErgoVR system will be presented, in the scope of two PhD works. In the Cognitive Ergonomics side, one of the works studied behavioral compliance with warnings and on the Physical Ergonomics side, the other work studied wayfinding. A short introduction of each specific field of study will be presented, followed by a summary of the work done where the main functionalities of the ErgoVR system were used. At the end, other studies that also used the system will be briefly enumerated.

2.4.1 Behavioral compliance with warnings studies

Warnings are an important safety communication because they inform people about the presence of a potential hazard and transmit information about what can be done to avoid or minimize undesirable consequences (Wogalter, 2006b). Thus, to be successful in their purpose, warnings must be effective. However, evaluating warnings effectiveness is a complex and controversial issue among researchers that suggest several evaluation criteria related to the underlying reasons why a warning fails to achieve the intended goal (Ayres, 2011). A warning can be considered effective if is able to switch user’s attention to itself, if is able to maintain user’s attention long enough so the embedded information can be processed and understood, if the communicated message is coherent with user’s attitudes and beliefs and if it is able to motivate the user to change his behavior accordingly to the instructions transmitted by the warnings for the given situation.

Warnings effectiveness is typically modeled as a linear set of stages (DeJoy, Cameron, & Della, 2006) that could be seen as bottlenecks, or obstacles, with the power to prevent the warning to fulfill their goals. There are several methodologies to evaluate warnings ability to prevail over each stage of processing. From a methodological point of view, although the behavioral compliance is often viewed as the gold standard measure of warning effectiveness, it is the most difficult to investigate because is limited by several constraints such as: the ethical and safety impossibility to deliberately expose participants to real risks; the rare occurrence frequency of events that could lead to injury in real world; the inherent difficulty of building laboratory sceneries that need to have a believable risk level, yet at the same time are safe (Glover & Wogalter, 1997). Other important aspect is the difficulty of direct control and manipulation of variables with accuracy and easiness in experimental conditions (Kalsher & Williams, 2006). To overtake such constraints researchers have typically assessed the measurement of warning effects at pre-behavior stages such attention (Wogalter & Vigilante, 2006), comprehension/memory (Hancock, Bowles, Rogers, & Fisk, 2006), among others, or assessed compliance behavior indirectly, using intentions to comply as a measurement (Wogalter & Dingus, 1999).

Although other measures are capable of evaluating important aspects relevant to warning effectiveness, the effects may not always be translated into behavior. Behavioral compliance is the primary measure of warning effectiveness (Kalsher & Williams, 2006; Silver & Braun, 1999; Wogalter et al., 1987). Compliance can be assessed in laboratory or field settings but involves, almost always, observation of what persons are doing. To promote nonbiased behavior from participants, these studies frequently adopt the incidental exposure experimental paradigm (e.g., Dingus, Wreggit, & Hathaway, 1993; Duffy, Kalsher, & Wogalter, 1995; Hatem & Lehto, 1995; Kalsher, Gallo, Williams, & Wogalter, 2000; Wogalter et al., 1987), in which participants are not pre-informed that the study concerns warnings. Another option for behavioral compliance measurement is to measure it indirectly, through cues or physical traces of behavioral compliance, such as checking later whether protective gloves had been used by indications of being stretched (Wogalter & Dingus, 1999). Epidemiological analysis (e.g., accidents databases) might also be used to measure indications of compliance. Measuring compliance is difficult due to the costs of effort, time, safety, and ethical considerations; therefore there has been a noticeable tendency for researchers to take an easier route by measuring a proxy for behavior, namely, reported motivation to behave through self-reported about what people would do in response to a warning (i.e. intentions to comply). Although they are linked to some extent with actual behavior, provide useful information, and offer insight on the processing involved, intentions are not the same and do not assure that effects can be translated into compliance behavior (Duarte et al., 2010).

In this context, with the technological evolution associated to interaction devices (e.g., HMDs, data gloves, motion sensors), in the majority of the cases associated with the game industry (e.g., game engines), some authors started to explore the potentialities of using Virtual Environments to evaluated the behavioral compliance with warnings, which are examples a pioneer study of Glover and Wogalter (1997), and more recently the studies of Shih, Lin and Yang (2000), Tang, Wu and Lin (2009) and Gamberini and colleagues (2003).

Although VR is suggested in these studies as an alternative with great potential, it is important to consider at the time of its adoption the trade-off between its advantages and disadvantages. The following is a summary of the main advantages and disadvantages of VR.

For this type of studies, the main advantages of VR are grouped in three topics: availability, safety and data provision, as described in Rebelo, Noriega, Duarte & Soares (2012). Regarding availability, VR makes available to researchers the access to different types of environments and contexts, even those that are most inaccessible and of conditioned access, allowing the manipulation of environmental (e.g., noise, lighting) and situational variables (e.g., presence of avatars exhibiting diverse behaviors) for systematic replication. It should also be noted the advantages associated with lower costs of development and carrying out of studies, both financially and temporal costs, when compared with the equivalent in real physical contexts, be it in laboratory settings or in the field. As for safety, VR allows safety in the interaction with environments, machinery and/or potentially dangerous products, without causing material and/or personal damages. At last, as to data provision, VR allows the collection of various types of data, either automatically through the software system (e.g., duration, distances, events) as through the observation of the participant's behavior (e.g., body/verbal language, biofeedback), with high internal validity (i.e., rigorous measurement of variables) and reasonable ecological validity (i.e., approximation to real world situations).

However, VR also presents some disadvantages, including adverse effects and technological constraints, with varying degrees of severity, which must be considered. It should be pointed out issues related with Virtual Reality Induced Symptoms and Effects (VRISE), technological issues and even personal factors. With regard to VRISE, defined by Cobb, Nichols, Ramsey and Wilson (1999), there are several included factors such as nausea, vomits, visual fatigue, headaches and disorientation, among others. As for the technological issues, they are related with displays limitations (e.g., limited field-of-view, latency which produces blurriness on movement), immersion (not all systems offer the same level of isolation from the outside world), navigation devices which most offer less natural forms of navigations and interaction devices which provide limited or unnatural forms of interaction with the VE, among others. Finally, it should be stressed some individual characteristics that can affect the quality of the experience with VR, such as the tendency/susceptibility for motion sickness, age (some studies suggest that the elderly are more susceptible to VRISE), and gender (some studies suggest that women suffer from motion sickness with greater frequency and severity than men). For more details, readers are referred to Rebelo, Noriega, Duarte and Soares (2012). It should be noted that with careful planning of the experimental procedure, the design of the VE and the required tasks, as well as the choice of the equipment that is best suited for the objectives of the study, it is possible to minimize the adverse effects mentioned herein.

Considering the current state of the art regarding the potentiality of VR, determining the contribution of this tool for this type of studies still requires more research, so Duarte (2011) proposed to conduct a study with the objective to determine the potential of immersive VR, as a methodological tool, to evaluate the behavioral compliance with warnings. To this end, it was evaluated the behavioral compliance with signs (i.e., cued and uncued), and emergency signs, that are static and multimodal/dynamic in environments that were visually favorable and unfavorable (i.e., through the manipulation of environmental lighting and visual chaos). Additionally, the behavioral compliance with the emergency signs (e.g., signs with indication of emergency exits) was evaluated during an emergency egress following an explosion and fire. From the combination of these variables resulted in five experimental conditions, two with visually favorable environment and other two with visually unfavorable environment, diverging as to the type of the sign, and, a neutral condition with a visually favorable environment and no sign present.

In this study, it is understood by static warning, ISO-type impressed warnings (ISO, 2011), with two panels (i.e., sign panel, comprised of symbol, color and background shape, and a text panel). By multimodal/dynamic warnings, it is understood the previous ones complemented with intermittent lights and a sound (i.e., beep), with two states (i.e., on and off) which are activated by a proximity sensor. Regarding the emergency exit signs, the same criteria is applied with the difference that they are activated by the explosion. The compliance was measured through the recording of the interaction of the button that were associated with the warnings (i.e., activate and deactivate), while the compliance with the emergency exit signs was measured through the correct first choice of the evacuation route.

The environment created for the simulation is compatible with an office building, with two main areas (i.e., rooms and escape routes). The rooms area is composed by four rooms (i.e., meeting room, laboratory, cafeteria and warehouse) and the escape routes area were composed by six “T”-shaped corridors with only one possible route. It was given to the participants a scenario where they would have to assume the role of a security guard in which they would do a routine end-of-day security check. In the environment there were written instructions that would indicate to the user the tasks to do (e.g., turn of machines). After entering in the warehouse, an explosion occurred, followed by a fire, beginning therefore the building evacuation phase. Since this environment was also used in the navigational interfaces comparative study, further details are described in Chapter III - Navigational Interfaces.

In making this assessment, the study sought to demonstrate the robustness of VR to measure variables whose effect on behavior has already been determined in real environment studies, in both laboratory or in the field. Additionally, several performance variables were measured (i.e., time, distance, pauses, average speed).

The immersive VR system ErgoVR supported the study, allowing, in terms of hardware, the integration of different interaction devices (i.e., HMD for visualization, motion sensors, joystick, and headphones, among others). The integration of these devices allowed for a more natural/spontaneous interaction including the possibility for the participants to move their left arm and hand to press the buttons, as well as allowing them to change their view perspective simply with the head movement, as they would do in the real world.

Regarding the software, the ErgoVR system allowed to program a sequence of events that were associated with the ability of participants to complete the task, such as, for example, turn on/off machines, open/close doors, activation/deactivation of the multimodal/dynamic signs by proximity, initiate the explosion/fire and associated sounds, spread the fire in order to "chase" the participant, forcing him to walk towards the exit. Besides that, the system collected automatically, the compliance and performance data, as described above. After the simulation, through the LogViewer component, the ErgoVR system provided extrapolated data, by participant and groups, such as interaction information (e.g., buttons pressed, detection of entry and exit of rooms or pre-defined areas and respective times, and activation of events, among others).

2.4.2 Wayfinding studies

Wayfinding, together with locomotion, are the components of the spatial navigation process (Montello, 2001, 2005). While locomotion refers the real-time part of navigation and occurs when people move successfully in the direction they intend without injuring themselves or moving into obstructions, wayfinding requires decision-making and/or planning process, involves some representation of the environment and aim to reach destinations which usually are beyond the current field of view.

The intentional process of finding one's way from an origin to a destination following a route is what defines wayfinding (Golledge, 1999). Human displacement is a directed and motivated activity which involves selecting specific paths in a complex environment. It is necessary to be able to identify the origin and destination point, to determine the angles of turns, to identify movement's direction and the segment length, to recognize points of reference (e.g., landmarks), in order to follow a successful route.

According to some authors (e.g., Carpman & Grant, 2002; Cubukcu & Nasar, 2003), wayfinding processes within complex buildings have been considered a key aspect by Managers, Architects, Interior Designers, Engineers and others professionals involved in planning these structures to enhance welfare of users of theses spaces.

Wayfinding behavior in the real world can be affected by several factors, such as explorations conditions (e.g., driving, walking), navigational tools (e.g., maps, signage), and environmental variables (e.g., light, color). According to Peponis, Zimring and Choi (1990), to understand how it occurs is still very difficult because, from a methodological point of view, experimental research in this field lacks control over the environment being examined, over the exposure time to the environment, and over the influence of the researchers themselves while observing the subjects. Furthermore, the high financial costs and time consumption in changing the environment accordingly to the study's needs are also an issue. As such, Virtual Reality has been considered for some experimental studies (e.g., Cubukcu & Nasar, 2003, 2005; E. Vilar et al., 2013; Elisângela Vilar, Rebelo, & Noriega, 2012), in order to overcome the methodological issues mentioned. Virtual Reality allows to analyze the human interaction with the built environment with more than the user's subjective opinions, by collecting objective data during the simulation (e.g., paths taken, choices made).

The wayfinding case studies that used ErgoVR as a tool and will be presented next, were based in decision taking and used two different types of methodologies. The first one (Study 1) used a methodology based in the instinctive decisions (psychophysics). The second one (Study 2) is based on a methodology of continuous navigation (or continuous interaction), where the decision taking is made in a more conscious level than in Study 1. Details that are not present in the next topics regarding this studies can be seen on (E. Vilar, Teixeira, Rebelo, Noriega, & Teles, 2012) for Study 1 and (E. Vilar et al., 2013) for Study 2.

a) Study 1

Environmental cues can influence decisions taken by visitors of certain complex buildings (e.g., hospitals, convention centers, university campus). That influence is the basis for the main objective of this study. It was hypothesized that, in the context of a simulated emergency egress, people prefer to move along either a wider and with more lighting corridor or to bear right.

To achieve the goal of this study, the ErgoVR system was used, most specifically the Decision Taking state. As described earlier, in topic 2.3.3 - Simulator, the Decision Taking state allows to test decision taking scenarios. Those scenarios can be static (no interaction from the user is allowed except the recording of the decision that was made) or dynamic (also records the decision that was made and allows the researcher to define a fixed path where the user would move along the scene). For this study, static scenarios were used. A set of virtual indoor hallways was presented to participants using a 3D projection. The sequence was presented using a constant stimulus method combined with a two-forced choice method. Three conditions were considered: *corridors width with same lighting*, *lighting enhanced in wider corridors* and *lighting enhanced in narrower corridors*. From these conditions, 27 "T-type" intersections representing two corridors were designed. Participants were exposed to two blocks of 112 trials, presented in a randomized order, where the corridors were repeated 8 times (except a specific corridor with equal width and lighting conditions for both directions that was repeated 16 times). The inter-stimulus duration varied randomly between 800 and 1000ms of duration. The participants could make their choice within the 1400ms that each corridor was presented. As soon as the participant made the choice, the inter-stimulus screen (gray screen with a black cube in the center) was presented.

Participants saw the stimuli in a 3D projection and made the choices by pressing a button on a gamepad. These devices could be used seamlessly with the ErgoVR system. The random variation on the inter-stimulus break duration as well as the recording of the choices made were possible due to the Decision Taking state of the ErgoVR system.

The findings of this study show that participants prefer wider corridors with the best results on an increment of width of 150cm. Participants also prefer to follow corridors that have more lighting. When both these variables are present, there is an almost 100% of choices made in that direction (wider corridor with more lighting). For the cases where the variables are concurrent (i.e., one corridor that is narrower with more lighting vs. a wider corridor that is darker), participants preferred the narrower corridor with more lighting.

b) Study 2

As a continuation of Study 1, this study intended to verify whether corridor characteristics (i.e., width, brightness and hallway intersection configuration) act as factors of attraction during an emergency egress situation. One of the main differences between this study and Study 2 is that participants are now in control of their movement inside the VE. This was possible by using the Decision Taking Simulation state of the ErgoVR system, which has a similar working mode as the Decision Taking state used in Study 1. The difference is that the participant can now use one of the different navigational interfaces that are supported by the ErgoVR system to navigate inside the VE. As such, for this study, the choice is made and recorded when the participant enters either one of the corridors, moment at which the inter-stimulus break screen is presented.

Participants had to make a choice in direction according to “T-type” and “F-Type” corridors, where the corridor’s width and brightness as well as the hallway intersection configuration were the independent variables. The different configurations of the corridors (57 experimental conditions) were presented to participants as a constant stimulus method combined with a two-forced choice method. The width of the perpendicular corridors varied in increments of 0.5m from 2m until 4m. The corridor brightness varied according to: a contrast ratio of 1:2 for every “T-type” corridor; a contrast ratio for the “F-Type” corridors where the front corridor is brighter than the side corridor; and a contrast ratio of 1:20 for the “F-Type” corridors where the front corridor is darker than the side corridor. Each participant were exposed to 4 blocks of 116 trials presented in a randomized sequence where the corridors were repeated 8 times (except a specific corridor with equal width and lighting conditions for both directions that was repeated 16 times).

Participants had, for each corridor (i.e., each stimulus), 7 seconds to make a decision, i.e., to navigate and reach the desired choice. As soon as the participant reached the decision point, the inter-stimulus break screen was presented (with a variable duration between 800 and 1000ms).

A joystick and a 3D projection were used in this study, which were supported natively by the ErgoVR system. Due to some of the particularities of the study, some of the configuration features of the ErgoVR system allowed the researcher to precisely define the Field-of-View (FOV) of the camera of the simulation, as well as other features as locomotion speed, sequence of corridors to be presented. These features were fundamental to guarantee that the image viewed by the participant was as if they were in the VE at the distance that they were of the projection screen (participants were seated 1.5m away from the projection screen).

The findings of this study show that participants chose left or right randomly as well as, in "F-Type" corridor, chose front or the side corridor randomly. Regarding the corridor width, participants favored wider corridors for "T-Type" corridors, but randomly in "F-Type" corridors. Participants also favored brighter corridors. For the cases where the width and brightness of the corridors are concurrent, participants chose deliberately narrower but brighter corridors in the "T-type" corridors and chose brighter corridors instead of those that were wider for the "F-Type" corridors.

2.4.3 Other studies

Other studies that used the ErgoVR system as a tool were made in the Ergonomics Laboratory. Some of these studies required the addition of certain functionalities that were not initially part of the ErgoVR system (i.e., possibility of presenting web pages as textures of objects inside of the Virtual Environment, with interaction with those webpages).

Some of the studies that used the ErgoVR system are: A study regarding the perception of the color of rooms for the elderly, where the rooms were compared using a digital support (using VR) and using the rooms printed on paper (Pacheco, Duarte, Rebelo, & Teles, 2010).

Another study used the ErgoVR system to assess the perception of people in an hospital room according to the presence of different elements (a chair, paintings, a plant and a window) in the room (Dinis et al., 2013).

Another work focused on optimization techniques for 3D models to develop VEs for the ErgoVR system, where the main example of application of those techniques was a hospital ward (Fernandes, 2013).

There was a study that created a VR prototype of a museum exhibit, constructed using ubiquitous technologies, to assess user experience (Ocampo, 2012) and another study that made use of VR to study user experience of information presented by the means of an interactive and dynamic infographic (Dadalto, 2012). Both these studies used the abovementioned feature of ErgoVR to present information in the form of a webpage, inside a VE.

A study was made that compared the wayfinding performance indoors (in a building), using vertical and horizontal orientation signage (Elisângela Vilar et al., 2012).

Another study was done regarding the influence of affordances in the decision taking in an everyday situation (Duarte, Vilar, Rebelo, Teles, & Almeida, 2011).

A study, using an eye-tracker and the ErgoVR system, was conducted to verify if the first eye fixations correspond to the decision made by the participants, in corridors (Noriega, Vilar, Rebelo, Pereira, & Santos, 2012).

Another study was also conducted regarding behavioral compliance with emergency egress signs in a conflicting situation, where the emergency sign was leading to the opposite direction of the direction given by an affordance of the environment (Ribeiro et al., 2012).

2.5 Conclusions

In this chapter it was described the use of the UCD approach for the development of a VR model for Behavioral compliance with warnings studies and for Wayfinding studies. This model is represented by the ErgoVR system. That system is composed by hardware and software. It should be noted that although the ISO 13407 (ISO, 1999) was followed in the development of the ErgoVR system, in the meantime that standard was replaced by ISO 9241-210 (ISO, 2010). At the time of writing this document, it was decided to maintain the reference to the previous standard since it was the standard that was used throughout the development of the project.

Although there are several iterative software development methodologies (e.g., scrum, crystal clear, extreme programming), they focus mostly on the programming stages of the process. Although all of them have specific stages for testing (unit testing as well as integration tests), the contact with the potential users is usually on a later stage of development. For the development of the ErgoVR system, a UCD approach was used where the potential users were involved in most of the stages of the iterative process. The UCD approach was more appropriate for this system than other iterative software development methodologies because the potential users of the system were researchers. These researchers were fundamental in guiding and prioritizing the type of functionality that the system needed to have as well as testing it in order to confirm that the system would fulfill their research projects' needs in the best possible manner. As such, the constant feedback gotten from the researchers allowed to orient the features and functionality development for that purpose. The constant and swift feedback from the users allowed that the necessary changes would be made in short and quick incremental phases, which provided, at similar pace, to the users a new version of the ErgoVR system that they could test and use. This allowed that each cycle of the UCD approach was short (ranging from a 1 day to at most 2 weeks on longer cycles, where more complex functionality had to be implemented).

This is visible by the work that was carried out (especially on the two case studies presented in topic 2.4 - Evaluation of ErgoVR), where it was possible to observe that the ErgoVR system was:

- Stable and reliable in the presentation of Virtual Environments;
- Able to collect all the intended variables;
- Appropriate to the different interaction devices (visualization and navigation) that were integrated with the system;
- Used by users without programming knowledge;
- Able to provide data outputs that could be personalized according to the study at hand as well as relevant extrapolated data.

Although the focus of the ErgoVR system development was mostly for behavioral compliance with warnings and wayfinding studies, it can also be used for other types of studies as presented in topic 2.4.3 - Other studies.

These conclusions are substantiated by the quantity and quality of the studies made that used the ErgoVR system as a tool, with most resulting in publications in conferences and journals. This is complemented with graduate, master's and PhD works.

Chapter III - Navigational Interfaces

3.1 Introduction

In this chapter it is presented a comparison study to verify if there is an influence of the used navigational interface on behavioral compliance with warnings in Virtual Reality (VR), as well as the evaluation of some performance metrics (e.g., distance, duration, pauses, average speed) and some subjective measures (i.e., sense of presence). Also, the development of a Walk-in-Place navigational interface is described in this chapter.

Virtual Reality has been used in many fields of study, particularly in human behavior research, to examine how people behave when facing certain situations. For some types of studies, a critical point to the effective use of this technological approach is to provide the users the means with which they could believe that they are in a place, even when they are physically in another, in a way to enhance the sense of presence (Witmer & Singer, 1998).

Many aspects of the VR system can influence the immersion and the sense of presence, such as the equipment used, the narrative context, and the quality of the Virtual Environment (VE) (Gorini, Capideville, De Leo, Mantovani, & Riva, 2011; Gutierrez et al., 2008). The navigational interface, which allows the participants to dislocate inside the VE can be one of those aspects.

A navigational interface to simulate walking is a device that is able to create an artificial sensation of physical walking and it is ideally equipped with three functions (Iwata, 2013): 1) the creation of a sense of walking while the true position of its user is preserved; 2) allowing the walker to change bearing direction; and 3) the simulation of uneven walking surfaces. Several different types of interfaces have been developed such a purpose, from interfaces usually made for games (e.g., de Haan, Griffith, & Post, 2008; Lapointe, Savard, & Vinson, 2011), passing through more complex system such as the CirculaFloor (Iwata, Yano, Fukushima, & Noma, 2005), or Walk-in-Place interfaces (e.g., Feasel, Whitton, & Wendt, 2008; Templeman, Denbrook, & Sibert, 1999; Wendt, Whitton, & Brooks, 2010), to real-walking interfaces such as omni-directional treadmills (e.g., Darken, Cockayne, & Carmein, 1997). However, each interface has advantages and disadvantages in regards to the fulfillment of the three functions mentioned by Iwata. For example, the CirculaFloor, which is a system based on moving squared platforms that move automatically to be in front of the participant when walking, and although it allows a participant to move in several directions, it requires some physical space and the participant can only make smaller steps, to give time for the platforms to move to the correct position. The main disadvantage of the omni-directional treadmills is the physical space required, although it is the navigational interface that provides more sensory information to the participant, since it allows the user to walk naturally. However, not all of the abovementioned navigational interfaces are able to provide enough sensory information as we have when physically walking.

Human sensory systems are able to provide information that allows us to create a spatial model of the environment we are in, as well as determine our place in that environment and how we move through it (Waller & Hodgson, 2013). Vision is the sensory modality that is richer and provides more spatial information, even when stationary (Waller & Hodgson, 2013). For perceptual tasks happening in real-time such as speed, distance and heading estimation, the optic flow appears to be sufficient to enable accurate spatial knowledge (Waller & Hodgson, 2013). However, for tasks that require tracking rotational changes of a person, visual information alone it is not enough and can influence the acquisition of spatial knowledge and the development of cognitive maps (Cánovas, Espínola, Iribarne, & Cimadevilla, 2008). For that, vestibular (for angular and linear accelerations of the head), proprioceptive and kinesthetic information (for position, orientation and movement of the musculature) are more suited (Waller & Hodgson, 2013). This type of information, if available, is presented in a different way when interacting with a VR system, thus compromising the experience of the user with the system. Vestibular information is given by allowing that the real movements of the head are reproduced as virtual movements of the camera within the Virtual Environment (VE), for example, by using a motion sensor. However, for proprioceptive information, it is required a navigational interface that could provide that type of information by allowing a person to walk normally and have that movement being reproduced in the VE.

For instance, in the study of the human wayfinding behavior, VR has been used to understand how people find their way from an origin to a destination. Most of the studies in this field use a joystick as a navigational interface (e.g., Conroy-Dalton, 2001; E. Vilar et al., 2013; Elisângela Vilar et al., 2012). Nonetheless, the physical cost (energy consumption) associated with walking may influence wayfinding within complex buildings (Hochmair, 2005; Pingel, 2010). As such, a study with a search-like type of task that allows active navigation can be influenced by the lack of proprioceptive information and energy consumption.

Studies on human behavior using VR are done in the Ergonomics Laboratory of the University of Lisbon, with focus on behavioral compliance with signs and warnings, and wayfinding within buildings, in both every day and emergency situations. For these types of studies, it is critical to promote the participants' behaviors which are closer to those they would have in the real world, in order to produce realistic data. So, allowing people to interact with the VE as they would interact with the real world (i.e., walking and rotating as they would in a real environment) could enhance the interaction quality and contributing to behavioral responses closer to those attained in real world research.

In this way, and regarding the studies of behavioral compliance with warnings and wayfinding that used the system described in this document, one question that remained open when they were developed was if the navigational interface used would affect, and how, the obtained results, i.e., if it would affect the observed behavior of the participants.

The behavioral compliance with warnings study presented in the previous chapter made by Duarte and colleagues (Duarte et al., 2013), used a Joystick as a navigational interface and as such participants were seated during the entire experiment. Participants could also move their heads to change the point of view inside the VE. However, no proprioceptive information directly related with walking was present.

As such, the main objective of this study is to verify if there is an influence of the used navigational interface on behavioral compliance with warnings in VR, as well as the evaluation of some performance metrics (e.g., distance, duration, pauses, average speed) and some subjective measures (i.e., sense of presence). This was done by comparing three navigational interfaces (a Joystick, a Nintendo® Balance Board and a Walk-in-Place interface). Since the interfaces have different forms of interaction, the comparison is made mostly between the hand-controlled interface (the Joystick) and the other two interfaces which are controlled by the lower-body. As such, the three navigational interfaces were compared while participants would interact with the VE used the Static Uncluttered condition of the work of Duarte and colleagues (Duarte et al., 2013). The Static Uncluttered condition was selected since it was the condition that is closer to a real working environment and also because it was the condition from which the other conditions of that work were created by manipulating some specific variables for that study.

The Nintendo® Balance Board (Nintendo, 2010) was selected as one of the navigational interfaces to test because it is an inexpensive force plate platform, made for games which is cheap and easily available. As suggested by Bartlett, Ting and Bingham (2014), the Balance Board can be used for low-resolution measurements, i.e., in the detection of differences in postural sway of greater than 10 mm (such as navigation in a VE where it is not required the level of precision of a laboratory grade force plate platform).

Riecke and colleagues (2010) compared participants on a navigational search task with rotations/translations controlled by physical motion or joystick. They concluded that allowing the user to control the simulated rotations with their own body can have significant benefits over mere joystick navigation. Also, they found that the real-turn mode they used was statistically equivalent to performance for actual walking suggesting that, for many applications, allowing full-body rotations without actual walking (e.g., a walk-in-place technique) can provide considerable performance benefits, even for complex and cognitively demanding navigation tasks. Also, Ruddle (2013) did a literature review where he identifies the types of interfaces that are more appropriate to different applications. In that review he states that VR applications where maneuvering is the most demanding aspect of navigation, will benefit from walking interfaces. A Walk-in-Place interface can be used in small spaces and although does not provide all of the proprioceptive feedback as a full-walking interface does, it allows the participants to change directions freely by allowing complete physical rotations. There are some studies (e.g., Peck, Fuchs, & Whitton, 2011; Ruddle, Volkova, & Bülthoff, 2013) that present test experiments of Walk-In-Place implementations when compared with other types of navigational interfaces (e.g., joystick) but none considered a real life-like situation with an emergency situation. Regarding the sense of presence with Walk-in-Place interfaces, Slater and colleagues (Slater, Usoh, & Steed, 1995) assessed the impact on presence of a Walk-in-Place technique and found that this sort of navigational interface can enhance the subjective rating of presence. Usoh and colleagues (1999) also mention that natural locomotion has been shown to be beneficial in terms of presence. For these reasons, a Walk-in-Place navigational interface was developed and selected as the second navigational interface to be compared with the Joystick. Further details on the navigational interfaces used in this study and how they work are given in topic 3.1.2 - Navigational interfaces.

3.1.1 Hypotheses and rationale

There are two different types of tasks (a search task and an emergency egress task) to be performed by participants in the VE, which allow to understand how the different navigational interfaces perform in those cases. As such, and for each of the navigational interfaces, the following dependent variables were collected: (1) behavioral compliance with warnings (in both areas); (2) other performance metrics such as distances, duration, pauses and average speed; and (3) sense of presence (subjective measures). More details regarding these variables are present in topic 3.2.3 - Variables. Gender differences were also analyzed for every variable.

Considering these metrics, and what was previously mentioned, the following effects are expected:

1. Expected effects on **Behavioral compliance:** Behavioral compliance with warnings/signs was the main dependent variable on Duarte's study and provides a measure of warnings' success (i.e., ability to prompt a given safe behavior). As long as the navigational interface does not pose any impairment in navigating inside the VE, it was hypothesized that navigational interfaces would not be affect behavioral compliance;
2. Expected effects on **Performance metrics**:
    - 2.1. For the interfaces that closer mimic the natural locomotion and have higher energy consumption (Balance Board and the Walk-in-Place) are expected:
        - 2.1.1. Lower total distance travelled than with the Joystick;
        - 2.1.2. More pauses and longer durations on those pauses than with the Joystick;
        - 2.1.3. Higher total duration of the simulation than with the Joystick (due to the increased number of pauses);
    - 2.2. Higher values for average speed are expected for the interface for which it is easier to start the movement and reach higher speeds faster (i.e., Joystick);

    2.3. Regarding each navigational interface, different results for the performance metrics (e.g., average speed) are expected for each area since the nature of the task of each area is different;
3. Expected effects on **Sense of Presence**:
    3.1. Higher sense of presence is expected for the Walk-in-Place interface since is the one that closer mimics the natural locomotion.

As such, this chapter describes the comparison test between the three navigational interfaces, in a behavioral compliance with warnings study. In the next topic, the navigational interfaces used for this study are discussed in more detail and how they work in conjunction with the rest of the VR system.

3.1.2 Navigational interfaces

In this topic, the three navigational interfaces studied are described and its integration with the ErgoVR system is explained. Since it was a system specifically developed for this study, the Walk-in-Place interface is described in more detail on how it was developed and how it was integrated into the ErgoVR system.

a) Joystick

The Joystick is a very common navigational interface used in for several studies (e.g., Peterson, Wells, Furness, & Hunt, 1998; Ruddle et al., 2013; Usoh et al., 1999) mostly because of its low cost, when compared with other alternatives, and its easiness of integration with VR systems. Joysticks are usually preferred when no extra interaction with the VE is required or it can be easily made with only one hand free, and also because most of the participants in such studies remain seated during the experiment, making the Joystick good fit for the study. However, the choice is usually made on a casual basis without a careful evaluation of performance, engagement or presence within the VE (Barfield, Baird, & Bjorneseth, 1998).

For this study, a Thrustmaster® USB Joystick was used (see Figure 15). While using the Joystick, the participant’s displacement in the VE is achieved by pushing the stick towards the desired direction of movement (forward or backwards). If a person pushes the stick to the left or right directions, the virtual body will rotate in the corresponding direction. A person can also make a composed movement by pushing the stick into the intermediate position of two directions, which would result in the combination of the two axes used (e.g., turning left while moving forward would require to move the stick forward and also to the left, to the northwest position). The Joystick axes have intermediate levels of state, with different values, depending on how far the stick is pushed. As such, the movement of the stick on each axis of the Joystick corresponds to different speeds of dislocation in the VE depending how far in the axis the stick is located.

Figure 15 – Thrustmaster® USB Joystick *(image obtained from the official website)*

b) Balance Board

The Balance Board (see Figure 16) is a game accessory created by Nintendo® (2010) for the Wii console system. However, it has been used for other uses in the scientific community as an inexpensive force plate platform, albeit not appropriate for studies that require high levels of accuracy (Bartlett et al., 2014). Several studies used the Balance Board to assess older adult's balance (e.g., Rendon et al., 2012; Young, Ferguson, Brault, & Craig, 2011) as well as for vestibular rehabilitation (e.g., Meldrum et al., 2012).

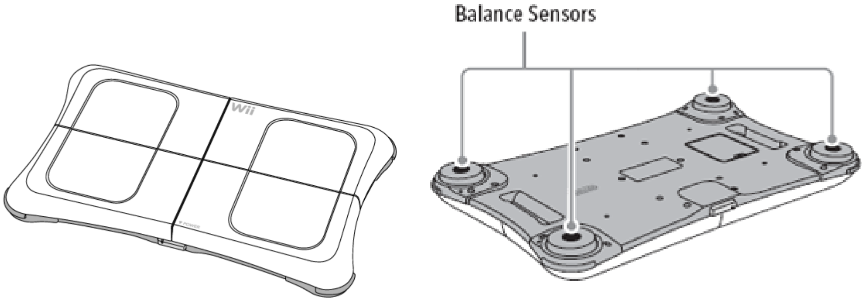


Figure 16 - Images of the Nintendo Wii Balance Board. Seen from above (left) and seen from the bottom (right). Images retrieved from Nintendo®'s official website and user manual.

The Balance Board is a rectangular shaped balance platform, which can be connected with a computer through Bluetooth®, with four pressure sensors in its corners. With those sensors it is easy to gather the weight and the center of balance of the user. The center of balance is the projection of the center of mass over the Balance Board platform.

The information given by the Balance Board can be used as a reference to create movement in the VE. For this study, what was used for the integration of the Balance Board in the VR system was similar to the *direct control of speed* mentioned by Hilsendeger and colleagues (2009). That is, leaning on the platform makes the navigation, by applying more pressure (i.e., by shifting their weight) on different areas of it. If the participant wants to move forward (or backward) in the VE, he/she just needs to apply more pressure on the forward (or backward) sensors of the platform. If the participant applies more pressure on the left or the right sensors of the platform, the virtual body will rotate over its own axis. Therefore, the forward or backward movements, plus the leaning left or right movement's combination produce a compound result of having the virtual body moving forward or backward while rotating left or right. The more weight that is applied into a certain direction, the faster is the corresponding movement inside the VE. In Figure 17, representations of the recognized movements are presented.

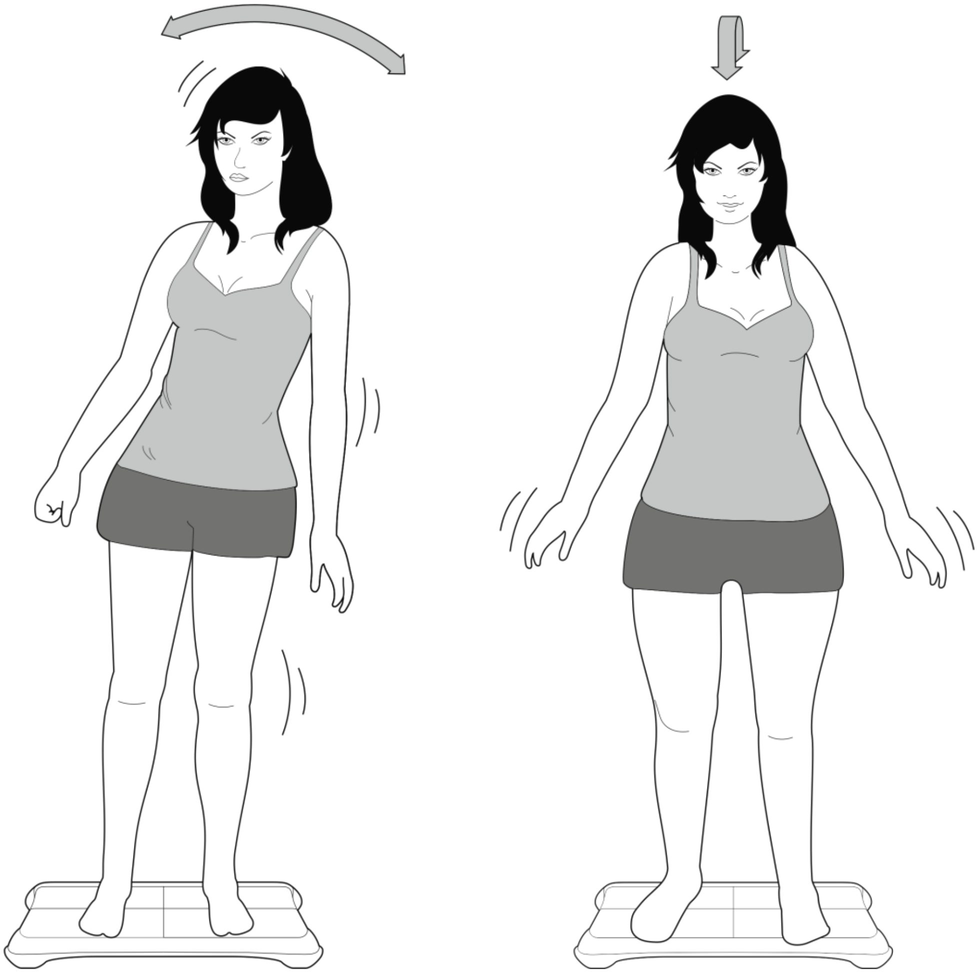


Figure 17 - Movement representation on the Balance Board

c) Walk-in-Place[14]

With the growth of studies on human behavior using VR, the need of navigational interfaces that are more natural and closer to moving in a real environment increases, as navigation can be considered one of the key tasks for the interaction with VEs (Bowman, Kruijff, LaViola, & Poupyrev, 2005). One solution to enhance the sensation of walking in VEs is a Walk-in-Place

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[14] Parts of this topic are from the following paper "Teixeira, L., Vilar, E., Duarte, E., Noriega, P., Rebelo, F., & Silva, F. M. da. (2013). Strategy for the Development of a Walk-In-Place Interface for Virtual Reality. In A. Marcus (Ed.), *Design, User Experience, and Usability. User Experience in Novel Technological Environments SE - 46* (Vol. 8014, pp. 419–426). Springer Berlin Heidelberg. doi:10.1007/978-3-642-39238-2_46"

interface, which provides users with a semi-realistic sensation (because people are marching rather than walking) of walking while moving in the VE, and without the need of large real physical space. Hence, users move up and down their foot as they were walking in the same place. This technique was introduced by Slater and colleagues (Slater et al., 1995), and since then it was used considering some different approaches. For a detailed review see (Terziman et al., 2010).

As pointed by Terziman and colleagues (2010), most of the applications consider the interaction with VEs and mainly the use of Head-Mounted Displays (HMD). As with other navigational interfaces, studies considering Walk-in-Place interfaces require the acquisition of the movement of the participant and to create a corresponding translation into movement inside the VE. Generally, motion trackers are used to capture the motion of body segments in order to be translated in movements inside the VE. Some studies tracked the head movements to predict and detect the steps (Razzaque, Swapp, & Slater, 2002; Slater et al., 1995; Usoh et al., 1999). The main disadvantage of this approach is that the movement direction is conditioned by the head direction, impeding users to look to a direction while moving to another.

To overcome this, other studies were conducted by tracking the lower body segments, such as the knees (Templeman et al., 1999), legs (Yan, Allison, & Rushton, 2004), and shins and heels (Feasel et al., 2008; Wendt et al., 2010). In the study carried out by Templeman and colleagues (1999), the distance of movement and direction of the legs were tracked by 6 Degrees of Freedom (DOF) trackers attached to the knees and the motion of legs was detected by force sensors placed on shoe insoles. Yan and colleagues (2004) used a hybrid acoustic-inertial 6DOF position and orientation tracking system with three sensors (two for the legs and one for the abdomen) and four sonistrips. For the study of Feasel and colleagues (2008), three magnetic 6DOF sensors were used, being two positioned on the users' heels and the other one on the chest for the direction. Motion capture cameras were used by Wendt and colleagues (2010). For their study, the user wears beacons for 6DOF trackers on his shins, which were tracked by cameras placed on the floor. The use of the Walk-in-Place technique was also adapted to be used only with a webcam to detect head movements, to be more used in limited field of view VR setups such as desktop VR (Terziman et al., 2010). For this case, participants could remain seated during the experiment. Although they only detect head movements, it is possible to walk, turn, jump and crawl. These examples have some disadvantages such as being too intrusive for requiring the use of several sensors, or require more expensive equipment (as some high performance motion detection cameras), which in turn usually requires larger physical spaces, or by only allowing the participant to be facing forward to the cameras, not allowing therefore the participant to make full rotation.

A Walk-in-Place interface could be the most suitable type of interface to be used in confined spaces and in studies about human behavior, since it provides proprioceptive feedback and can provide vestibular feedback when allowing participants to fully rotate. As mentioned before, this type of feedback can increase the sense of presence of participants, leading users to act in VEs as they would in the real world, giving more ecological validity to the studies.

It is also important to notice that most of the Walk-in-Place interfaces found in the literature use more than one sensor to track the user's displacement and rotation. Also, depending on the laboratory settings available, the use of motion capture through cameras is an alternative that can become impractical in small spaces since it requires a clear line of sight between the cameras and the markers on the participant, as well as a high number of cameras to be able to detect markers that might be hidden in certain angles (overlapping information). Furthermore, in the solutions that use motion sensors, they generally use magnetic sensors. This type of sensors suffers of interferences from magnetic fields, which also limits the laboratory settings configuration.

Considering this, one of the main objectives of this implementation of the Walk-in-Place technique is to have a fully functional interface that uses only one inertial orientation sensor (3DOF). The movement of walking in place can be captured only by the changes in rotation of the leg, therefore not requiring a 6DOF motion sensor.

Development

The Walk-in-Place interface developed for this study comprises a single inertial sensor (i.e., XSens MTx) that is placed above the user's knee. In a first approach, the main measurement considered to represent the tracked leg movement into the displacement and direction within the VE was the amplitude differences between the rotation values given by the sensor (as can be seen on Figure 18), considering the rotations in each axis by using the corresponding Euler angles (i.e., yaw, pitch and roll). Since there are variations of values in every axis when a participant moves the leg, it was decided to limit the detection of movement by analyzing each axis independently. As such, for the detection of movement of the leg going up and down, only the axis that represents the pitch was used and the yaw axis was used to detect changes in direction. Broadly speaking, the Walk-in-Place interface works by detecting variations on the sensor orientation values, in different axes. Further, the system detects the frequency at which the person lifts and lowers the leg to determine the speed value to be applied to the virtual body. In order to do that, the use of the Walk-in-Place interface requires to be used in two phases: *Calibration* and *Data Collection.*

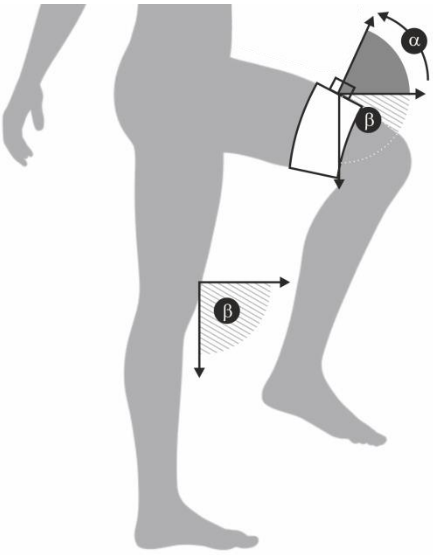


Figure 18 - The angular measurements used to translate the tracked body into the movement within the VE. α represents the difference between the rotation values given by the sensor when the leg is lifted.

Calibration phase. Since each individual has different kinetic features, the Walk-in-Place interface needs to be calibrated for each participant. The calibration process involves, after positioning the sensor above the participant's knee, asking the participant to make the walk movement in the same place during a controlled amount of time (i.e., five seconds).

In Figure 19, a dimensionless representation of the data from the pitch axis is presented. The movement of the leg is clearly represented by two moments: 1) when the leg is lifted (represented by the α area); 2) when the leg is the rest position (represented by the β area). The calibration phase is responsible for the definition of those two areas. A Gaussian Mixture Model (GMM) is used to define the two areas by using an Expectation-Maximization algorithm to fit the GMM to the collected data during the calibration. After fitting the GMM, the system has information on the interval of values that are considered the area of values where the leg is lifted (α) and the area of values where the leg is in the rest position (β).

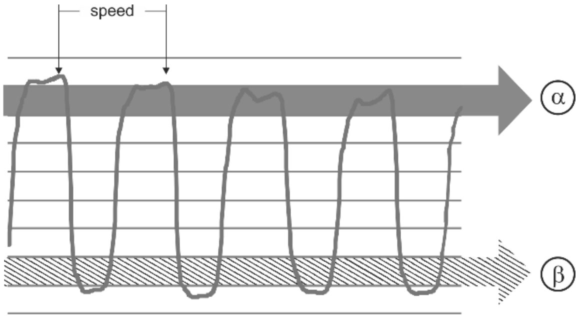


Figure 19 - The graphic model of the translated body movement tracked by the sensor with the two areas which represent the lifted (α) and rest (β) position of the leg of a specific participant (dimensionless data because it changes per participant).

Data Collection. After the calibration phase, the system already has the expected intervals of orientation values for a specific participant, and can use that as a base for detecting the movement and change the current speed to the virtual body in the VE. The speed is given by the frequency that the participant lifts and lowers the leg, resulting in a higher speed with higher movement frequency. The real-time detection determines the frequency at which the data values flow from the β area to the α area and back to the β area. The system attributes each data that receives from the motion sensor into a category (leg is lifted, leg is in the rest position, in between) and depending on the previous data points, it starts counting the time until the data points return to that category to be able to attribute a corresponding speed value.

To avoid abrupt changes in speed in the VE (especially in the beginning of the movement and when stopping), the current speed value is calculated taking into consideration a group of previous values to filter and smooth the resulting speed value.

As mentioned before, the direction of the movement is given by the changes on the Yaw axis. The reference direction of the motion sensor is collected during the calibration moment. However, during the walking movement, there are deviations of values on that axis. Therefore, to have the most correct value for the direction, a smoothing filter is applied to the incoming stream of data, providing the final direction.

The action of “Moving backwards” is also a challenge to be addressed while developing a Walk-in-Place interface. Very few efforts have been done to solve this issue and it was not found in the literature any reference to how this behavior is considered when using a Walk-in-Place interface. When walking in a real environment, a person rarely needs to walk backwards, because the corrections are made before the collision happens. However, in VR, due to different factors such as lack of control or confidence in working with the navigational interfaces, small corrections of movement might be necessary, requiring therefore taking a few steps back. The solution that was considered for this study was to use a secondary interface (i.e., a Ring Mouse which can be seen in Figure 20) that allowed participants to move backwards, at a constant speed, while they were pressing a button on the device. This solution was considered to simplify the learning process of the participants, since other solutions considered memorizing certain gestures or specific leg positions to do the same backwards movement.

Figure 20 - Genius® Ring Mouse interaction device

3.2 Method

3.2.1 Design of the study and protocol

An experimental study with a between-subjects design with the navigational interface as the independent variable, was developed. As such, the study was comprised of three experimental conditions, one for each of the navigational interfaces (i.e., Joystick, Balance Board and Walk-in-Place). Behavioral compliance, performance variables and sense of presence were the dependent variables for this study. More details regarding the variables used in this study are presented in topic 3.2.3 - Variables.

The experimental session was divided in four stages: (1) signing of consent form and introduction to the study; (2) training; (3) simulation; and (4) questionnaire.

1. In the beginning of the session, participants signed a consent form and were advised that they could end the experiment at any time. They were tested for color-blindness with the Ishihara test (Ishihara, 1988). In this part of the experimental session they were also introduced to the study and to the equipment they were going to use in order to learn how they would use it to interact with the simulation. Participants were told that the testing of a new VR software was taking place, which could automatically capture data regarding their interactions within the VE. This was told in order to reduce the possibility of any bias from the participants while trying to deliberately perform better with the specific navigation interface.
2. In the training session, participants were placed in a training VE to familiarize with the equipment. Participants were told that they could explore the area freely until they felt able to control the navigational interface. Also, there was a button in the training environment, and the researcher asked participants to interact with it. If the participant could achieve these goals without difficulties, the researcher would consider that the participant was able to do the simulation.
3. The scenario was an end-of-day security routine check where participants had to follow messages present in the environment with specific tasks and where they could interact with six buttons in the VE. Participants were told that they were in a new part of the building for them, and that they were there to replace a co-worker that got sick in the morning. However, before that co-worker went home, he left written messages in the different rooms with instructions to what needed to be done. After the researcher told the cover story, there was no dialog between the researcher and the participant until the end of the simulation. The simulation ended when participants reached the end point of the VE or after 20 minutes (the researcher would stop the simulation if the participant seemed lost in the environment).

4. After the simulation, participants replied a questionnaire regarding their experience with the VE and the interaction quality, were debriefed and thanked for their participation in the study.

3.2.2 Virtual Environments

This section describes the Virtual Environments for the training and simulation stages. These environments are the same used in the study of Duarte and colleagues (Duarte et al., 2013). The Virtual Environments described in this section were modeled in Autodesk 3dsMax v2009 and exported through the free plugin OgreMax v1.6.23 to be presented by the ErgoVR system.

a) Training

The training VE was small and simple and its main objective is to allow participants to familiarize themselves with the equipment. The researcher would ask certain tasks to be performed to guarantee that the participants were feeling apt and in control of the equipment to go to the simulation.

The environment contained a small room with a cylindrical column in the center of it and a connection to a zigzag type of corridor (see the top view plan in Figure 21). In the room there were also two posters with some text and a button that would start playing an ambient sound when pressed. Figure 22 and Figure 23 depicts a view of the small room with the posters and the button.

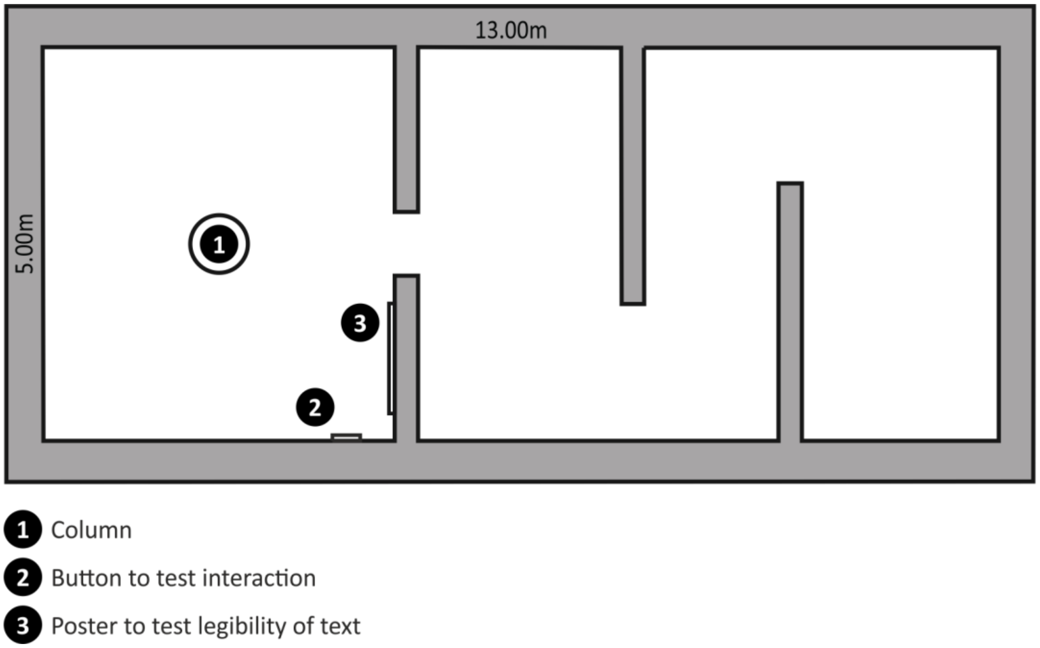


Figure 21 - Top View of the Training Virtual Environment

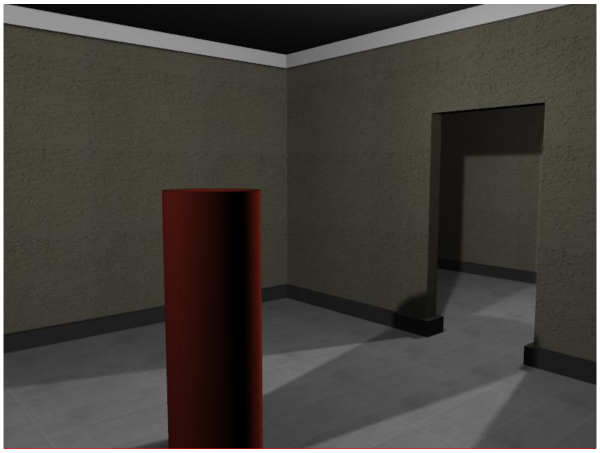


Figure 22 - Training environment's room with the column at its center

Figure 23 - View of the posters and button on the Training environment

Participants were told that they could explore the area freely until they felt able to control the navigational interface. After allowing participants to try to understand the controls alone, the researcher would ask that they would go to the end of the zigzag corridor and come back to the room to move around the pillar in both directions, without stopping. After that, the researcher asked participants to read the posters out loud. Participants were then asked to press the button and they were encouraged to ask questions with any doubts that they might have. When asking for pressing the button, the researcher said that button was an example of a type of object that could be interacted with.

If the participants could achieve these goals without difficulties, the researcher would consider that the participants were able to do the simulation.

b) Simulation

The VE comprises two areas, which involve different types of tasks. The first area, *Area 1 – Rooms*, represent a search task, where participants needed to follow the instructions written on messages and find the next room to accomplish the task mentioned in the message. The second area, *Area 2 – Escape Routes*, represents an emergency egress task, where participants need to reach the emergency exit of the building.

Area 1 – Rooms was composed of four rooms (meeting room, laboratory, cafeteria and warehouse), each measuring 12 x 12 meters. The rooms were interconnected by two perpendicular, symmetrical corridors, and the rooms were circumvented by another corridor. The corridors were 2 meters wide. The circumventing corridor had an exit that lead to the escape routes area and it also had several doors which could not be opened by the participants.

There were six buttons, each associated to a safety sign, placed on the walls distributed in *Area 1 – Rooms*. Participants were directed to 3 of the signs (nominated as cued *signs*) through the messages with instructions placed on boards in each room. The other 3 signs (nominated as uncued signs) were not mentioned on the messages. The buttons changed color and had an auditory feedback to reinforce the action of pressing the button.

For the Joystick and Balance Board conditions, the interaction with the buttons in the VEs was made with a motion sensor that was placed and strapped in the participant's wrist. When participants moved their arm in any direction, a hand cursor would be presented on the screen which moved according to the direction the participant moved the arm. Then, when the cursor was over the object that the participants wished to interact they would do a flick movement with their wrist to activate the action associated with the object. For the Walk-in-Place condition, participants used a Ring Mouse to move the cursor and interact with the buttons as they would with a mouse. Since participants already used the Ring Mouse to allow them to move backwards, this was selected to reduce the number of interaction devices that participants would have to understand and interact at the same time.

An orientation signage system was also designed in order to help participants find the respective rooms. These signs were wall-mounted directional signs, in panels, with pictorials, arrows and written information. Figure 24 to Figure 27 present images from the VE for *Area 1 – Rooms*.

Figure 24 - Entrance of the Cafeteria with the horn warning and respective button

Figure 25 - Cafeteria view with the board with the message on the left and the Valve gas on the right side

Figure 26 - Entrance of the Warehouse with the button regarding Polluted Atmosphere

Figure 27 - View of the fire inside the Warehouse, which starts when the participant enters the Warehouse

Area 2 – Escape Routes consisted in a sequence of interconnected T-type intersections, where only one option in each intersection would lead to the next one, and ultimately to the end of the simulation. Each intersection was marked by a capital letter label, so participants would not feel disoriented, thinking that they were always returning to the same location. The Exit signs were placed at each intersection to mark the routes of egress and their dimensions were 30 by 15 cm and were placed in the wall at 2.20 m from the floor. Figure 28 to Figure 31 present images of the VE for *Area 2 – Escape Routes*.

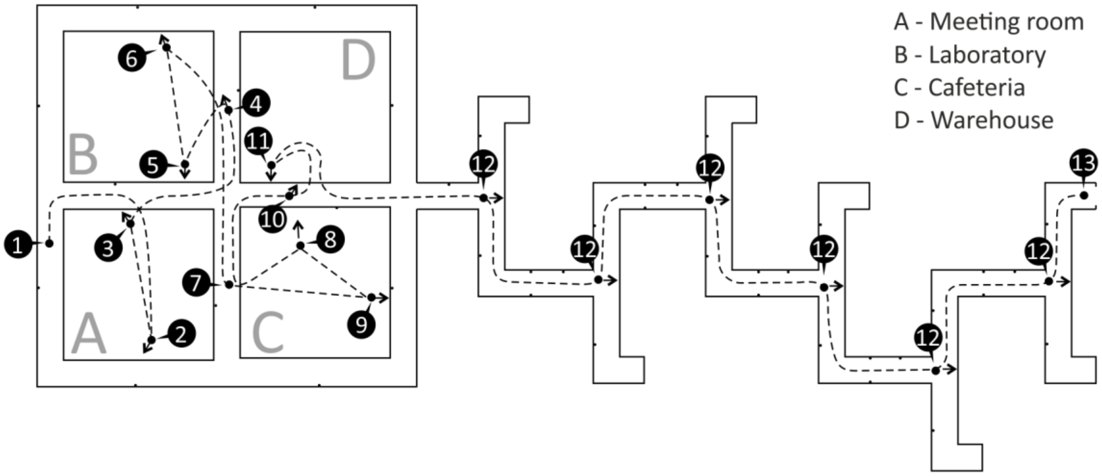
Figure 28 - View of the entrance to Area 2 - Escape Routes, just outside the Warehouse

Figure 29 - View of the first Intersection, with the visible exit sign

Figure 30 - View of an Intersection with the letter for that Intersection

Figure 31 - View of the exit point (end of the simulation)

A top view of the complete environment, with the sequence of events that participants would have to do is presented in Figure 32.



❶ Beginning

❷ Instruction: Check for water cups on the top of the tables. If you find any, please leave a message in the Cafeteria. Then go to the Laboratory room and turn on the security system

❸ Warning: Mandatory to disconnect before leaving the room

❹ Warning: Laser in operation, do not enter before turning it off

❺ Warning: Security System

❻ Instruction: Now go to the Cafeteria and turn the gas off

❼ Warning: Sound warning, mandatory to warn before entering

❽ Instruction: After the gas is shut off go to the Warehouse and cut the energy to the machine room

❾ Warning: Gas valve

❿ Warning: Inhalation hazard. Start air extractor before entering the room

⓫ Warning: Cut energy to machine room

⓬ Emergency exit signs

⓭ End

Figure 32 - Top view and sequence of events of the Virtual Environment

Participants would start in point 1. At this point, participants were already told the cover story and adverted that they should look for the first instruction in the Meeting Room (Room A in the image). In point 2, a written instruction in a wall screen asked participants to look for water cups on the tables and to leave a message in case they would find some. If there were no cups on the tables, they should direct themselves to the Laboratory to turn off the security system. On point 3 it was posted the first uncued sign, saying that it was mandatory to turn off the music before leaving the room (complying with this warning would stop the ambient music that was playing). The warning present on point 4 was not analyzed in this study. Participants entered the Laboratory and on their left there was the security system (point 5) accompanied by the respective cued sign. On point 6 there was the second instruction that directed participants to the Cafeteria to turn off the gas valve. At the entrance of the cafeteria (point 7), the second uncued sign was posted, which said that it was mandatory for participants to warn before entering the Cafeteria (a horn sound would play if the button was pressed). Inside the Cafeteria, the gas valve and its respective cued sign was posted in point 9, and in point 8 the third instruction directed participants to the Warehouse in order to turn off the energy to the machines room. At the entrance of the Warehouse, the third uncued sign warned participants that the atmosphere was polluted and that they were required to press the button before entering the Warehouse. If the participant pressed the button, a ventilation sound would start and the Warehouse door would open. As soon as the participant entered an explosion sound occurred followed by a fire. At this point participants should start to escape the building and direct themselves to *Area 2 – Escape Routes* (the door for this part only opened when the fire started). On point 11 there was the last cued sign (the energy shutdown). Focus of fire also appeared on the adjoining corridors of the Warehouse entrance to direct participants to the escape routes door. Once in the escape routes, participants had emergency exit signs on the walls (in the locations pointed by number 12). As it can be seen in the top view of the VE, there is only one correct path to reach the end (point 13, represented by a door leading to outside).

3.2.3 Variables

As mentioned before, the independent variable for the study is the navigational interface which has three categories (i.e., Joystick, Balance Board and Walk-in-Place) as described in topic 3.1.2 - Navigational interfaces. The dependent variables of this study are behavioral compliance variables (i.e., compliance with uncued, cued and exit signs), performance variables (i.e., *Duration*, *Distance*, several variables related with the *Pauses*, and *Average Speed*), and sense of presence variables (evaluated after the simulation).

Regarding the behavioral compliance variables, the *compliance with uncued signs* is given by the number of pressed buttons associated with the warnings present in the environment that were not present in the instructions (there were three warnings for this situation). The *compliance with cued signs* is given by the number of pressed buttons associated with the warnings signs present in the environment that were mentioned in the instructions (there were three warnings for this situation). The *compliance with exit signs* is given by the number of correct choices in the intersections which is given by following the exit signs in *Area 2 – Escape Routes*.

Regarding the performance variables, *Duration* is the time spent, in seconds, in the simulation. *Distance* is the total traveled distance during the simulation. A *pause* was considered as the interval of time while the participant remained stationary in the VE during a minimum duration of 2 seconds. This limit was implemented to exclude momentary hesitations that could be caused for example by difficulties using the navigational interface (Conroy-Dalton, 2001). Several variables related with the *Pauses* were considered, namely *Number of Pauses* during the simulation, *Maximum duration of pauses* which is the maximum duration that a participant remained stationary during the simulation, and *Median duration of pauses* which is the median of the duration of all the pauses given by the participant in the entirety of the simulation. *Average speed* is given by the distance travelled over the simulation duration, in meters per second. It was considered after removing the pauses durations from the total simulation time.

The sense of presence variables are the result of the grouping of several questions of the questionnaire, described in the next topic.

a) Questionnaire

The questionnaire was presented post-interaction and comprised 36 questions, where two were of open-ended questions (i.e., age, occupation), five were multiple-choice questions (i.e., gender, videogame and Virtual Reality experience) and the remaining 29 were questions with a 7 point Likert-scale. The questions were separated into the following categories: Quality of the sensorial experience of the simulation, Quality of the interaction in the Virtual Environment, Distraction Factors, Realism Level, Notion of Time, Environment “pollution”, Global evaluation of the simulation, and Perceived danger and likelihood of injury. Some of the items of the questionnaire were adapted from the Witmer and Singer Presence Questionnaire (Witmer & Singer, 1998). Based on the those items, the sense of presence variables are *Quality of Sensorial Experience* (QSE), *Quality of Interaction* (QI), *Quality of Interaction for the Navigational Interface* (QINI), *Distraction Factors* (DF), *Realism Level* (RL), *Notion of time* (NT) and *Enjoyment* (ENJ). The relevant items of the questionnaire regarding the variables of the sense of presence are presented next, in Table 1.

Table 1 - Presence and enjoyment questionnaire items

	Item	Score
1.	**How would you classify the overall level of sensory stimulation experienced during the simulation (e.g., involvement of your senses in the virtual experience)?**	QSE
2.	**To what extent did the visual stimuli make you feel “inside” the VE?**	QSE

	Item	Score
3.	**To what extent did the auditory stimuli make you feel "inside" the VE?**	QSE
4.	**To what extent could you identify the sounds present in the VE?**	QSE
5.	**To what extent could you locate the sounds in the VE?**	QSE
6.	**To what extent could you visually explore the VE?**	QSE
7.	**To what degree was it easy to dislocate through the VE, by using the navigational interface (e.g., how easy was it for you to get to a certain point in the VE)?**	QI/QINI
8.	**To what degree could you control your displacement by using the navigational interface (e.g., how accurately could you position/stop yourself at the desired place)?**	QI/QINI
9.	**How quickly did you manage to adapt to the displacement, by using the navigational interface?**	QI/QINI
10.	**At the end of the simulation, how do you classify your displacement performance in the VE, by using the navigational interface?**	QI/QINI
11.	**To what degree was the looking behavior, offered by the system, natural (e.g., when you wanted to see something, in the VE, you moved your head in that direction)?**	QI
12.	**To what degree could you control the looking behavior (e.g., the capacity to direct your head, with precision, to a certain direction)?**	QI
13.	**To what degree was the execution of the virtual hand movements natural (e.g., when you wanted to touch the buttons, in the VE, did you move your hand in that direction)?**	QI
14.	**To what degree did you have control over the movements of the virtual hand (e.g., the ability to operate, accurately, the buttons in the VE)?**	QI
15.	**To what extent were you conscious of the HMD's presence during simulation?**	DF
16.	**To what extent did the form of navigation (joystick) cause distraction in the performance of the required tasks?**	DF
17.	**To what extent did the quality of the image displayed of the VE affect the performance of the required tasks?**	DF
18.	**To what extent, during the simulation, were you aware of what was happening around you, in the real world (e.g., be aware of sounds from the real world)?**	DF
19.	**To what degree is the simulation, you have just experienced, real?**	RL
20.	**To what extent do you consider your experience in the VE to be different from your experience in the real world?**	RL
21.	**Were you involved in the simulation to the extent that you lost track of time?**	NT
22.	**How would you rate your level of enjoyment in the simulation?**	ENJ

Note. QSE = Quality of Sensorial Experience; QI = Quality of Interaction; QINI = Quality of Interaction for the Navigational Interface; DF = Distraction Factors; RL = Realism Level; NT = Notion of Time; ENJ = Enjoyment.

The *QSE* variable takes into account the sensory experience that participants had (visual and auditory), the *QI* variable consists on the interaction aspects of the simulation (interaction with the navigational interface, the change of the visual perspective and the control of the virtual hand for the interaction with the buttons), the *QINI* variable is the subset of the *QI* variable which regards only the interaction with the navigational interface. The *DF* variable takes into account the elements that could affect the participant's performance, such as discomfort or limitations on the use of the equipment as well as external factors. The *RL* variable is connected to the similarities of the simulation with the real world, the *NT* with losing the track of time and finally, *ENJ* is related with the overall enjoyment of the simulation.

Each Likert-type question had three anchor points (i.e., beginning, middle and end of the scale). Depending on the question, the anchor labels varied. A summary of those labels is presented in Table 2. The full questionnaire is presented in Annex B - Questionnaire.

Table 2 - Anchor labels for the Likert-type questions

Beginning (1)	**Middle (4)**	**End (7)**
Very low	Average	Very high
Very low	Reasonable	Very high
Very little	Average	Very much
Never	Sometimes	Always
Very slow	Average	Very quick
Very bad	Reasonable	Very good
Very short	Average	Very long
None	Some	Completely

3.2.4 Sample

The participation in this study was voluntary, although restricted by an eligibility criteria, which was assessed in a short recruitment interview. The eligibility criteria to participate in this study were as follows: have between 18 and 35 years old; be fluent in the Portuguese language; have normal sight or have corrective lenses; have no color vision deficiencies which was tested with the Ishihara Test (Ishihara, 1988); not have mobility impairments; report being in good physical and mental health (e.g., not suffering from illnesses as epilepsy, heart conditions, seizures, among others that could be aggravated by the participation in the study); if female, she must not be pregnant. All participants completed an informed consent form which can be seen in Annex A – Consent Form.

A total of 123 people participated in this study. Due to diverse events such as simulator sickness (13 people, 10.6%), and equipment, energy malfunctions, external interruptions or the participants wanted to stop (20 people, 16.3%), a group of 33 participants were excluded from the final sample.

Consequently, this study's sample comprises 90 participants, equally distributed in gender and number by the three experimental conditions. Participants declared that they have not used the Balance Board interface nor a Walk-In-Place type of system before.

Participants had between 18 and 29 years old for the Joystick condition (*M* = 21.1, *SD* = 2.83), between 18 and 34 years old for the Balance Board condition (*M* = 21.8, *SD* = 3.38) and between 18 and 33 years old for the Walk-In-Place condition (*M* = 24.4, *SD* = 4.65), as it can be seen in Table 3.

Table 3 – Sample's Age descriptive statistics, by experimental condition

	Minimum Age	Maximum Age	Mean	SD
Joystick	18	29	21.1	2.83
Balance Board	18	34	21.8	3.38
Walk-In-Place	18	33	24.4	4.65

a) Experience with videogames and VR simulators

Participants were also asked about their experience with videogames and VR simulators. These questions are important because of the relationship of experience with videogames and spatial performance (e.g., Feng, Spence, & Pratt, 2007; Okagaki & Frensch, 1994) and the ability to interact with navigational interface (e.g., Rosenberg, Landsittel, & Averch, 2005; Rosser et al., 2007) as well as in the promotion of videogames typical behaviors. These questions were used to build a control variable to homogenize the sample according to it. The questions and respective results are presented next.

Question*: "What is your actual experience with videogames (e.g., computer games, X-Box®, Playstation® and Wii®)?"*

Answer options: *(1) I never played; (2) I play sporadically; (3) I play between 1 hour and 10 hours per week; (4) I play between 10 hours and 20 hours per week; (5) I play between 20 hours and 30 hours per week; (6) I play more than 30 hours per week.*

In Table 4 it is possible to see that the majority of participants (61.1%) play sporadically, followed by participants that play between 1 hour and 10 hours a week (24.4%). There was a small group of participants that stated that played between 10 hours and 20 hours per week (6.7%) and even a smaller group who played between 20 hours and 30 hours per week (2.2%). Only 5.6% of participants stated that have never played videogames and none of the participants played videogames for over 30 hours per week.

Table 4 - Sample distribution regarding the participants' experience with videogames, by experimental condition

	Experimental Condition			Total
	Joystick	Balance Board	Walk-in-Place	
Never played (1)	2	2	1	**5** (5.6%)
Sporadically (2)	18	17	20	**55** (61.1%)
1 - 10h per week (3)	8	9	5	**22** (24.4%)
10 - 20h per week (4)	2	2	2	**6** (6.7%)
20 - 30h per week (5)	0	0	2	**2** (2.2%)
>30h per week (6)	0	0	0	**0** (0%)
Total	30	30	30	**90** (100%)

Participants that play a certain types of videogames, especially action and adventure games, can have a more direct influence over behavior and therefore present different levels of performance when compared with other participants that do not play this type of videogames, because the interaction type and mechanics of such videogames are similar to the ones presented in the simulation of the study that was conducted. As such, participants were asked if they had experience with that type of videogames, and, if so, what would be their preferred gaming profile (first-person vs. third-person videogames).

***Question**: "Are you a frequent player of action/adventure videogames (more than 7 hours per week, in the last 2 months)?"*

***Answer options**: Yes/No.*

As it can be seen in Table 5, the majority of participants (88.9%) are not frequent players of action or adventure videogames. Only 11.1% participants play this type of videogames.

Table 5 - Sample distribution for participants that are frequent players of action/adventure videogame

	Experimental Condition			Total
	Joystick	Balance Board	Walk-in-Place	
Yes	4	1	5	**10** (11.1%)
No	26	29	25	**80** (88.9%)
Total	30	30	30	**90** (100%)

The participants that replied positively to the previous question also replied a question regarding their gaming profile (first-person vs. third-person videogames).

Question: *"If you replied yes to the previous question, please select your gaming profile"*

Answer options: *(1) First-person (e.g., Doom, Quake); (2) Third-person (e.g., Tomb Raider); (3) Both.*

In Table 6 it is possible to see that from the participants that are frequent players of action or adventure videogames, 4.4% consider that they have a First-person type of gaming profile, another 4.4% consider to have a Third-Person gaming profile and lastly, 5.6% of participants consider that they fit in both gaming profiles.

Table 6 - Sample distribution for gaming profile preference for frequent players

	Experimental Condition			**Total**
	Joystick	Balance Board	Walk-in-Place	
First-person	2	0	2	**4** (4.4%)
Third-person	2	1	1	**4** (4.4%)
Both	3	0	2	**5** (5.6%)
Total	7	1	5	**13** (14.4%)

Regarding the participants' experience with VR simulators, in the last two years, participants were asked three questions, presented next.

Question: *"Did you experience, over the past 2 years, simulators that use VR glasses?"*

Answer options: *(1) Never; (2) At least once; (3) Two or more times.*

Results, presented in Table 7, show that the majority of participants (97.8%) never tried simulators that use VR glasses, 8.9% tried at least once and only 3.3% tried two or more times.

Table 7 - Sample distribution regarding previous experience with VR simulators that use VR glasses

	Experimental Condition			**Total**
	Joystick	Balance Board	Walk-in-Place	
Never	26	27	26	**79** (97.8%)
At least once	3	3	2	**8** (8.9%)
Two or more times	1	0	2	**3** (3.3%)
Total	30	30	30	**90** (100%)

Question: *"Did you experience, over the past 2 years, simulators that use platforms/seats with motion synchronized with projected images?"*

Answer options: *(1) Never; (2) At least once; (3) Two or more times.*

Results, presented in Table 8, show that most of the participants (78.9%) never tried simulators that use platforms with motion, 14.4% tried at least once and only 6.7% tried two or more times.

Table 8 - Sample distribution regarding previous experience with VR simulators that involve platforms with motion

	Experimental Condition			**Total**
	Joystick	Balance Board	Walk-in-Place	
Never	21	26	24	**71** (78.9%)
At least once	6	4	3	**13** (14.4%)
Two or more times	3	0	3	**6** (6.7%)
Total	30	30	30	**90** (100%)

Question: *"Did you experience, over the past 2 years, simulators that use both processes simultaneously (VR glasses plus platforms with motion)?"*

Answer options: *(1) Never; (2) At least once; (3) Two or more times.*

Results, presented in Table 9, show that most of the participants (93.3%) never tried simulators that use both processes (VR glasses plus platforms with motion), only 3.3% tried at least once and also another 3.3% of participants tried two or more times.

Table 9 - Sample distribution regarding previous experience with VR simulators that involve both modalities (VR glasses and platforms with motion)

	Experimental Condition			**Total**
	Joystick	Balance Board	Walk-in-Place	
Never	26	29	29	**84** (93.3%)
At least once	2	1	0	**3** (3.3%)
Two or more times	2	0	1	**3** (3.3%)
Total	30	30	30	**90** (100%)

3.2.5 Apparatus

This experimental study required the following equipment:

1. A computer with an Intel® Core™2 Quad Processor Q6600 (8Mb cache, 2.40GHz), 8GB of RAM and with a NVIDIA Quadro® FX 4600 was used to connect all the relevant equipment and to run the simulation.
2. A computer monitor, from LG®, model W2453V, was used as the monitor that allowed the researcher to see what the participant was seeing.
3. A Head-Mounted Display (HMD) from Sony®, model PLM-S700E was used. This HMD presents the VE at a 800x600 pixels resolution, with a color depth of 32bits, with a refresh rate of 60Hz and with a Field of View (FOV) of 30° Horizontally, 22.5° Vertically and 38° Diagonally.
4. A pair of wireless stereo headphones from Sony®, model MDR-RF800RK were used to allow participants to hear the sounds presented in the VE. Although the headphones are stereo, it was possible to understand the relative position from where the sounds were coming in the environment.
5. Two types of motion sensors were used. Two magnetic motion sensors from Ascension-Tech®, model Flock of Birds, were used to capture the head and hand movements. The Flock of Birds is a 6 DOF (Degrees of Freedom) tracker, giving position and orientation of the sensor, at a refresh rate up to 144Hz. These sensors have a static accuracy of 1.8mm RMS for the position and 0.5° for the orientation. Also, at a distance of 30.5cm from the transmitter, the static resolution of the sensors is 0.5mm in the position and 0.1° in the orientation. The other type of motion sensors used was an XSens XBus Kit with one XSens MTx, which was used for the Walk-in-Place interface. The MTx is an orientation motion sensor with a static accuracy for the roll and pitch of less than 0.5° and for the heading of less than 1°, with a dynamic accuracy of 2° RMS and an angular resolution of 0.05°.
6. Only for the Walk-in-Place condition, a Genius Ring Mouse was used to allow participants to interact with the buttons in the VE and to allow them to walk backwards if they needed. Since the Walk-in-Place interface only allows to move forward and changing direction, an alternative was necessary to allow participants to make small backward correctional movements. That was allowed by pressing one of the buttons of the Ring Mouse, which allowed participants to move backwards at a constant speed while they pressed the button.
7. Participants were filmed for the entirety of the interaction with the VR system with 3 Bosch WZ14 Integrated Day/Night Video Cameras and the simulation image they were seeing in a Bosch Video Recorder model Divar MR. Also, and since the room was dark, another video camera from Sony®, model DCR-SR36, was used in Night Vision, to allow the research to see the participants interaction. This was more important in the training session, where the researcher could advise the participants on how to interact with the devices if they were having difficulties.

8. As for the navigational interfaces, a Thrustmaster® USB Joystick was used for the Joystick condition, a Nintendo® Balance Board was used for the Balance Board condition and the XSens Bus with one XSens MTx (mentioned earlier) was used for the Walk-in-Place condition.
9. For the Balance Board and Walk-in-Place conditions, participants were in a platform where they had a circular handle bar that they could hold. The platform's base was a square with 107 cm of side. The top of the circular handle bar was at 95 cm from the base of the platform. The inside of the circular handle bar had a diameter of 90 cm and the handle bar itself had 7 cm of width as it can be seen in Figure 33.

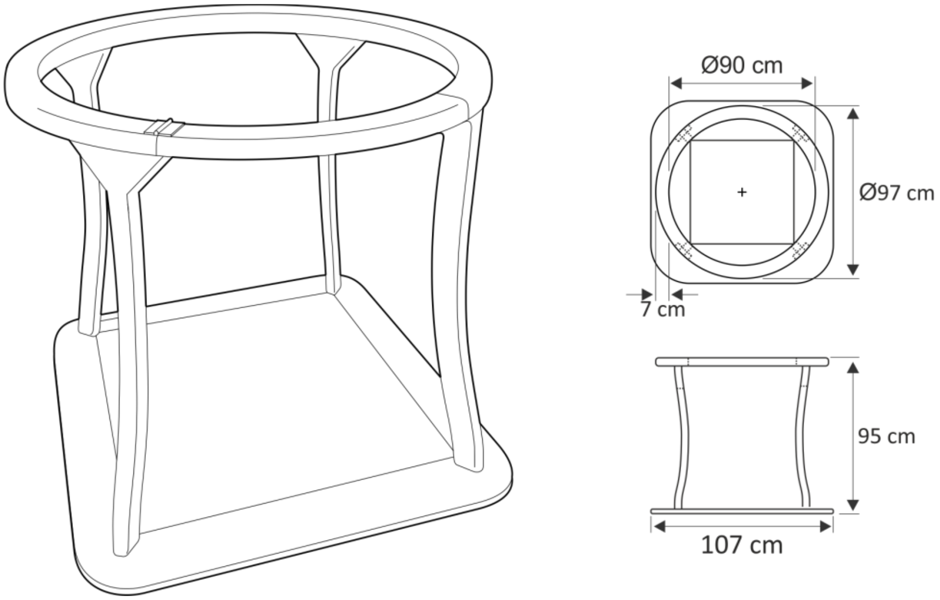


Figure 33 - Virtual Reality platform for navigational interfaces

3.2.6 Experimental facilities

The VR unit of the Ergonomics Laboratory of the Faculty of Human Kinetics of the University of Lisbon was used to collect the data. Figure 34 depicts the top view of the VR unit which is comprised of two interconnected rooms, where in Room 2 the training and simulation stages took place and in Room 1 the remaining stages (i.e., introduction of the study, questionnaire). Since the nature of the navigational interfaces used is different, it required a different configuration of Room 2. As such, for the data collection of the Joystick condition, the room configuration used is depicted in Figure 34. For the other two conditions (Balance Board and Walk-in-Place), the Room configuration used is presented in Figure 35.

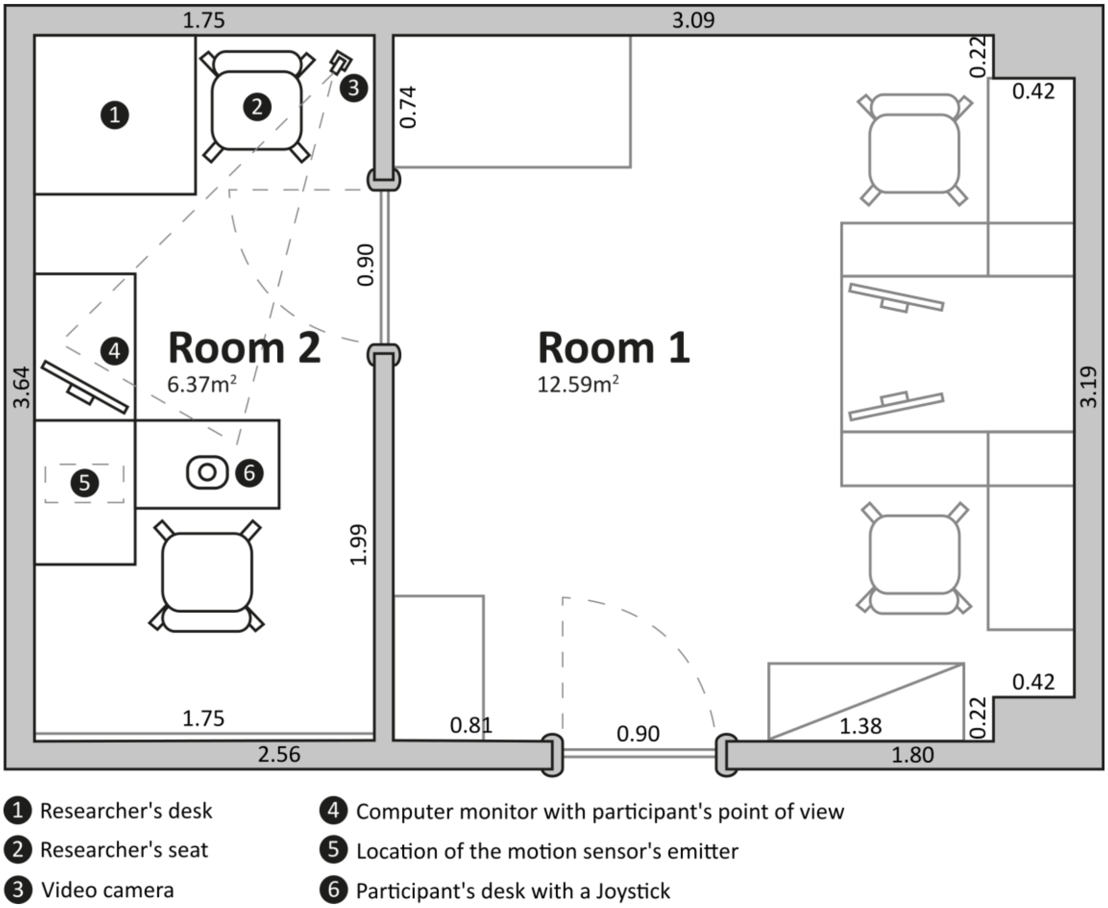


Figure 34 - Top view of the experimental facilities for the Joystick condition (units in meters)

During the experimental sessions, Room 2 was kept dark and as silent as possible, with the lights off and the door closed, in order to increase the level of immersion by reducing the amount of possible external elements for the participants. The researcher was in Room 2 for the entirety of the procedure for the participant’s safety and to perform the necessary interaction with the simulation computer. The researcher was able to see what the participants were seeing in a second computer monitor. Also, three Bosch WZ14 video cameras recorded the participant’s activity as well as the synchronized image of the VE that the participant was observing.

For the Joystick condition, participants remained seated for the entire procedure. For the Balance Board and Walk-in-Place conditions, participants were standing in the platform.

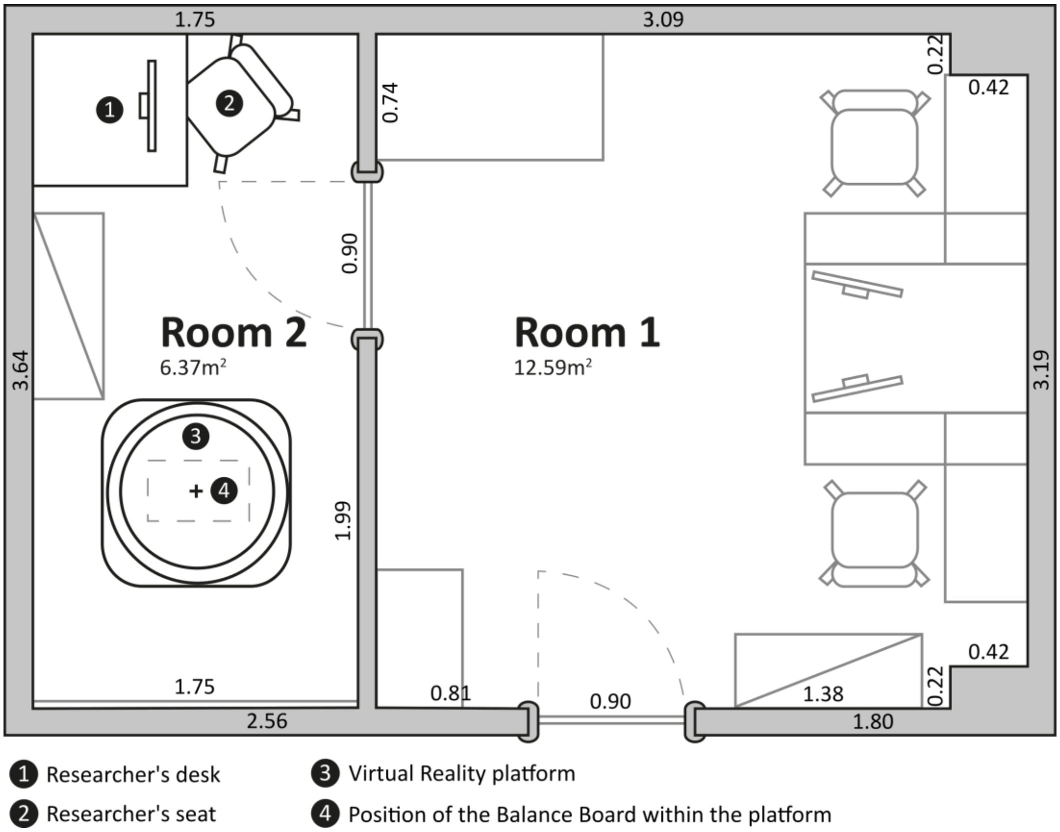


Figure 35 - Top view of the experimental facilities for the Balance Board and Walk-in-Place conditions (units in meters)

3.3 Results and Discussion

This topic presents and discusses the results attained in the experiment. The results refer to: (a) behavioral compliance (evaluated by the *compliance with uncued signs*, *compliance with cued signs* and *compliance with exit signs* variables); (b) performance variables (evaluated by the *time*, *distance, pauses – number and duration –* and *average speed* variables); (c) sense of presence; and (d) simulator sickness. The possibility of gender differences was also analyzed. The results are always presented regarding *Area 1 – Rooms* and *Area 2 – Escape Routes*.

The statistical analysis was conducted in IBM SPSS Statistics (v. 20) with the statistical significance level set at 5%. Due to the type of variables (ordinal) involved violation of normality assumptions, the Kruskal-Wallis (one-way analysis of variance by ranks) test was used to compare the different navigational interfaces (*Joystick*, *Balance Board* and *Walk in Place* interfaces) concerning the behavioral compliance variables (*compliance with cued signs*, *compliance with uncued signs* and *compliance with exit signs*) and performances variables *Duration*, *Distance*, and *Pauses*. For the *Average Speed* variable, a two-way mixed ANOVA with repeated measures test was used to evaluate the effects of the navigational interface (independent factor) and the area (repeated measures factor). Also, for each performance variable, it was analyzed if a *Gender* effect was present.

To facilitate reading the results, a brief summary with the main findings is presented at the beginning of each topic.

3.3.1 Behavioral compliance

Summary: *This topic reports the results from the analysis of the Behavioral compliance. Behavioral compliance is a composed variable integrating: (a) compliance with uncued signs; (b) compliance with cued signs; and (c) compliance with exits signs, according to the different areas of the environment, which provided different types of tasks (a search task for* Area 1 – Rooms *and an emergency egress type of task for* Area 2 – Escape Routes*). It was expected that if the participants did not had problems of navigation caused by a particular navigational interface, the Behavioral compliance would not present statistically significant differences depending on the navigational interface used. The results show that there are no statistical significant differences between the different navigational interfaces for the Behavioral Compliance variables. Although not statistically significant, it is possible to observe that the Walk-in-Place interface had higher values, for the* compliance with uncued signs *and* compliance with exit signs *variables, than the other two navigational interfaces. For the* compliance with cued signs *variable the Walk-in-Place had the same value as the Balance Board. A Gender effect was not found.*

For this study, behavioral compliance was analyzed according to the *compliance with uncued signs*, *compliance with cued signs* and *compliance with exits signs* variables among the three experimental conditions, i.e., for each one of the navigational interfaces. The *compliance with uncued signs* and *compliance with cued signs* variables are related to the task in *Area 1 – Rooms*, while the *compliance with exits signs* variable is related to the task in *Area 2 – Escape Routes*.

As previously described, while carrying out the task, participants had seven buttons in the VE that they should press, where three of them were uncued signs and three were cued signs. Cued signs were mentioned in the written instructions that were posted throughout the VE, whilst uncued signs were not mentioned on those instructions. On *Area 2 – Escape Routes*, the fire already started and participants had to exit the building, complying with the exit signs (i.e., following the indicated directions) on the environment.

a) Compliance with uncued signs

To verify the effect of the Navigational Interface in the Behavioral compliance, the Kruskal-Wallis was performed. The results of this non-parametric test showed that there is not a statistical significant effect of the Navigational Interfaces in the compliance with uncued signs ($\chi^2(2, 90) = 2.01$, $p = 0.366$).

Although no statistically significant differences were found, it was possible to observe that the Walk-in-Place interface had slightly higher values of compliance *with uncued signs*, as it can be seen in Figure 36.

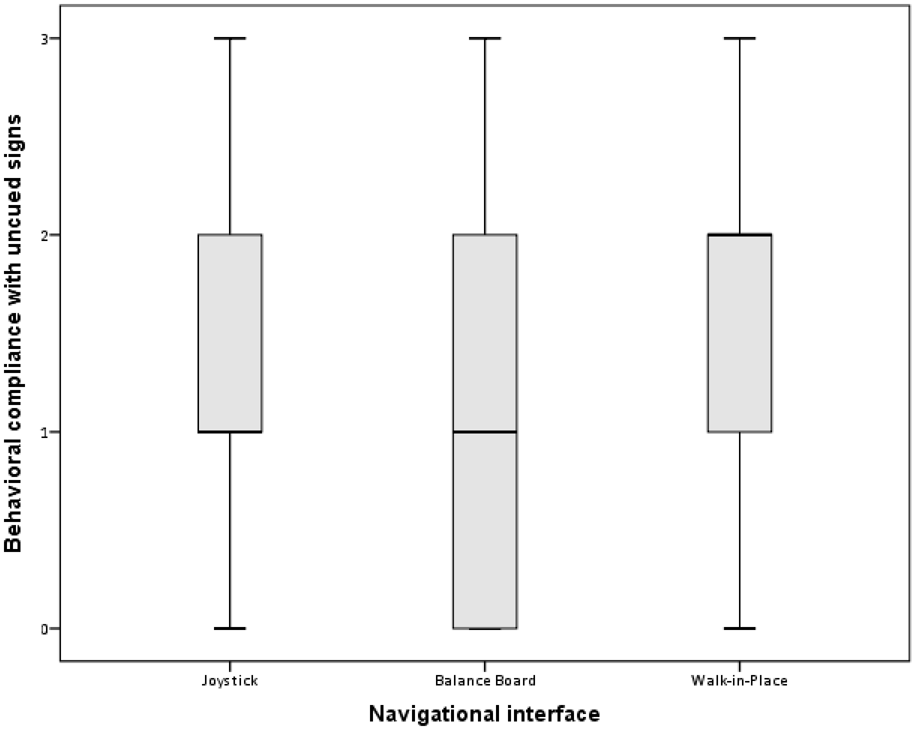


Figure 36 - Boxplots for the behavioral compliance with uncued signs variable, according to the Navigational Interface

b) Compliance with cued signs

The results of the Kruskal-Wallis test showed there is not a statistical significant effect of the Navigational Interface in the compliance with cued signs ($\chi^2(2, 90) = 5.83$, $p = 0.054$). Since the (asymptotic) *p*-value is in the threshold of significance, a Monte-Carlo exact test, with a 99% level of confidence and 100,000 samples was applied, resulting in a $\chi^2(2, 90) = 5.83$, $p = 0.053$ (lower bound = 0.051 and upper bound = 0.055).

Contrary to what was observed concerning the *compliance with uncued signs* for the Walk-in-Place interface (where a tendency for a higher compliance was present, although not statistically significant), in the case of the *compliance with cued signs*, that tendency is higher for the Joystick. Furthermore, the variability of results for the Walk-in-Place interface is higher than with the other navigational interfaces, as it can be seen in Figure 37. Interestingly, except for the outliers, most of the Balance Board participants complied with two of the three cued signs.

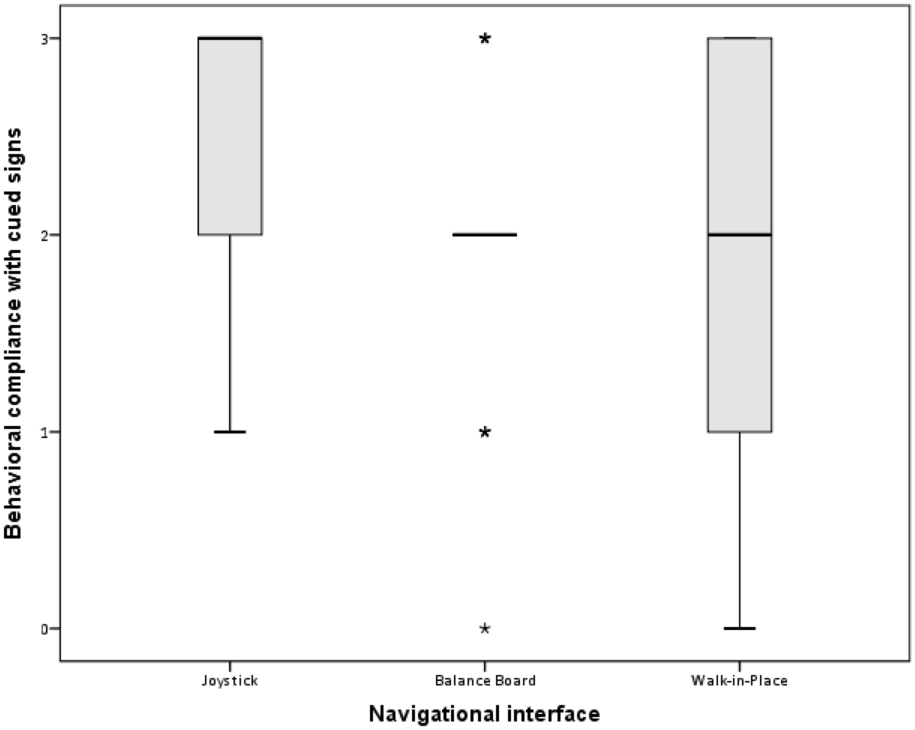


Figure 37 - Boxplots for the behavioral compliance with cued signs variable, according to the Navigational Interface

c) Compliance with exit signs

The results of the Kruskal-Wallis test showed that there is not a statistical significant effect of the Navigational Interface on the compliance with exit signs ($\chi^2(2, 90) = 3.30$, $p = 0.192$). Looking at the boxplots in Figure 38 it is possible to observe that variation of correct choices was higher with the Walk-in-Place interface than with the other, although no statistical significant differences were found.

By observing Table 10 it is also clear that there is a higher percentage of participants that took the correct decision at the intersections (i.e., following the indicated directions) with the Walk-in-Place (except for Intersection B). Also, the first Intersection had a higher percentage of participants that made the correct decision with the Walk-in-Place interface (97%) than with the Balance Board (73%) and with the Joystick (87%). Intersection E was the corridor that had a higher level of participants with the incorrect choice.

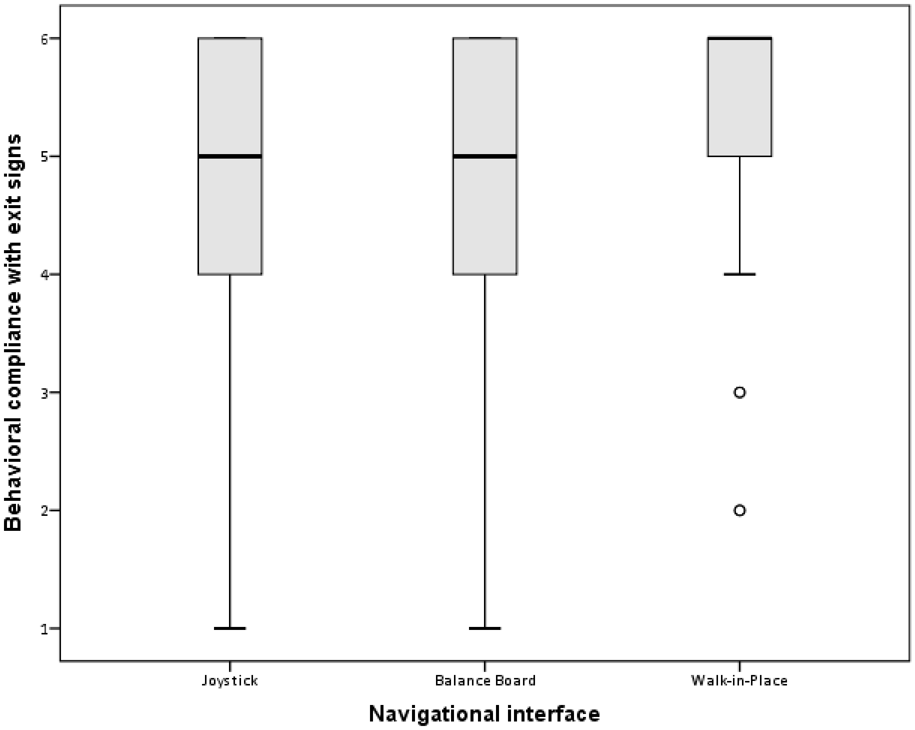


Figure 38 - Boxplots for the behavioral compliance with exit signs variable, according to the Navigational Interface

Table 10 – Frequency of correct decisions at the t-shaped intersections, by experimental conditions

	Experimental Condition					
	Joystick		Balance Board		Walk-in-Place	
Intersections	#	%	#	%	#	%
A	26	87%	22	73%	29	97%
B	23	77%	25	83%	24	80%
C	22	73%	26	87%	27	90%
D	24	80%	23	77%	26	87%
E	21	70%	21	70%	24	80%
F	22	73%	23	77%	26	87%

Note: # = number of correct decisions (N = 30)

Despite no statistical significant differences were found between the navigational interfaces regarding the *compliance with exit signs*, it is possible to observe that there is a lower variability of values for participants that used the Walk-in-Place interface, and the median value was the highest. It is worth noting that the percentages of correct decisions for the first intersection were much higher with the Walk-in-Place (97%) than with the Joystick (87%), or the Balance Board

(73%). Also, for every intersection (except Intersection B), the Walk-in-Place interface presented a higher percentage of participants that made the correct choice. These results might be an indicator of an effect of the navigational interface (especially the Walk-in-Place) in tasks similar to the emergency egress task required to accomplish in *Area 2 – Escape Routes*.

d) Gender differences

Due to the type of variables (ordinal) involved, to evaluate if there were any *Gender* differences for the Behavioral compliance variables, the Mann-Whitney U tests were conducted using Gender as the grouping variable. For either *compliance with uncued signs* (U = 894, W = 1929, *p* = 0.320), *compliance with cued signs* (U = 933, W = 1968, *p* = 0.490) and *compliance with exits signs* (U = 972, W = 2007, *p* = 0.728) variables, no statistically significant differences were found between males and females, so the behavioral compliance was not influenced by *Gender*.

3.3.2 Navigational interface performance

Summary: *This topic reports the results from the analysis of the performance-related variables according to the Navigational interfaces. Those variables are* Duration*,* Distance*,* Pauses *(number and duration) and* Average Speed. *As with the* Behavioral compliance *variables, these variables were evaluated according to the different areas of the environment. Since the navigational interfaces are different in terms of type of interaction, it was expected that differences would be found in terms of* Duration *and* Distance *while accomplishing the task, being the interfaces that closer resemble the natural locomotion movement to have lower values in terms of* Distance *and higher values in the* Duration *due to making more pauses. The navigational interfaces that would require more energy consumption would present a higher number of pauses since participants might use pauses as a mechanism to manage effort. Regarding* Average Speed*, it was expected that the navigational interfaces in which the start of motion would be easier/quicker to make (start moving, stopping, changing speed) would present higher values of* Average Speed*. It was also expected that since the tasks in each area had a different nature, the task would affect the* Average Speed*. Results show that there are statistical significant differences for the* Duration*, where Joystick participants did the simulation in less time than the other participants, in both areas. Regarding* Distance*, the Walk-in-Place participants travelled less distance than the other participants for* Area 1 – Rooms *and there were differences between the Walk-in-Place and the Balance Board participants in* Area 2 – Escape Routes*. For the* number of Pauses*, Joystick participants paused fewer times than the other participants. In terms of duration of pauses, Walk-in-Place participants paused for longer periods of time in Area 1 – Rooms than the other participants. However, in Area 2 – Escape Routes, Joystick participants despite having less pauses, they pauses for longer periods of time. Since differences were found in the number and duration of pauses among the*

different navigational interfaces, Average Speed *was considered by removing those pause durations from the total duration of the simulation, per participant.* Average Speed *is statistical significantly different in each area (i.e., for each type of task) and also between the different navigational interfaces for each type of task. No* Gender *effect was found for any of the abovementioned performance variables.*

For this study, navigational interface performance-related variables were analyzed. Those variables are *Duration*, *Distance*, *Pauses* (number, maximum and median duration of the pauses) and *Average Speed.* As with the *Behavioral compliance* variables, these variables were evaluated according to the different areas of the environment, in the three experimental conditions, i.e., for each one of the navigational interfaces.

Since the navigational interfaces are different between each other in terms of type and mean of interaction, it was expected that differences would be found in the *Duration* and *Distance* variables, with the interfaces that closer resemble the natural locomotion movement to have lower values for *Distance* and, due to a higher number of pauses, higher values for the *Duration*. Also, it was expected that, the navigational interfaces that would require more effort would present a higher number of pauses since participants could use pauses as a mechanism to manage the energy consumption associated with the effort required to accomplish the task. Regarding *Average Speed*, it was expected that the navigational interfaces where the start of motion would be easier/quicker to make (start moving, stopping, changing speed), i.e., the Joystick, would present higher values of *Average Speed* and that since the tasks in each area have a different nature, the task would affect the *Average Speed.*

a) Duration

On Table 11, the descriptive statistics are presented per area and for each one of the Navigational Interfaces. It is clear that, for the *Duration* variable (given in seconds), the Joystick has the lowest values, followed by the Balance Board and the Walk-in-Place for *Area 1 – Rooms* and *Area 2 – Escape Routes*.

Table 11 - Descriptive statistics for the *Duration* variable, in the two areas (in seconds)

		Mean	SD	Minimum	Maximum
Area 1 - Rooms	*J*	461.96	150.88	278.41	949.47
	BB	644.28	183.53	366.52	1059.6
	WiP	716.53	199.09	419.89	1397.49
Area 2 - Escape Routes	*J*	52.95	22.03	29.98	111.6
	BB	102.58	59.74	54.98	335.09
	WiP	112.84	55.85	46.68	269.24

Note: J – Joystick, BB – Balance Board, WiP – Walk-in-Place

On Figure 39 and Figure 40 it is possible to observe the variability of the *Duration* values, where it is clearly visible that the variability of values is higher with the Balance Board and the Walk-in-Place interfaces than with the Joystick. The difference between the navigational interfaces is more pronounced in *Area 2 – Escape Routes* than in *Area 1 – Rooms*. As mentioned before, each area involved tasks with different natures and that could be one of the reasons why the difference is more pronounced in one area. Another possible reason could be the fact that *Area 2 – Escape Routes* is further in the simulation and as such participants could be more at ease with the navigational interfaces at that point.

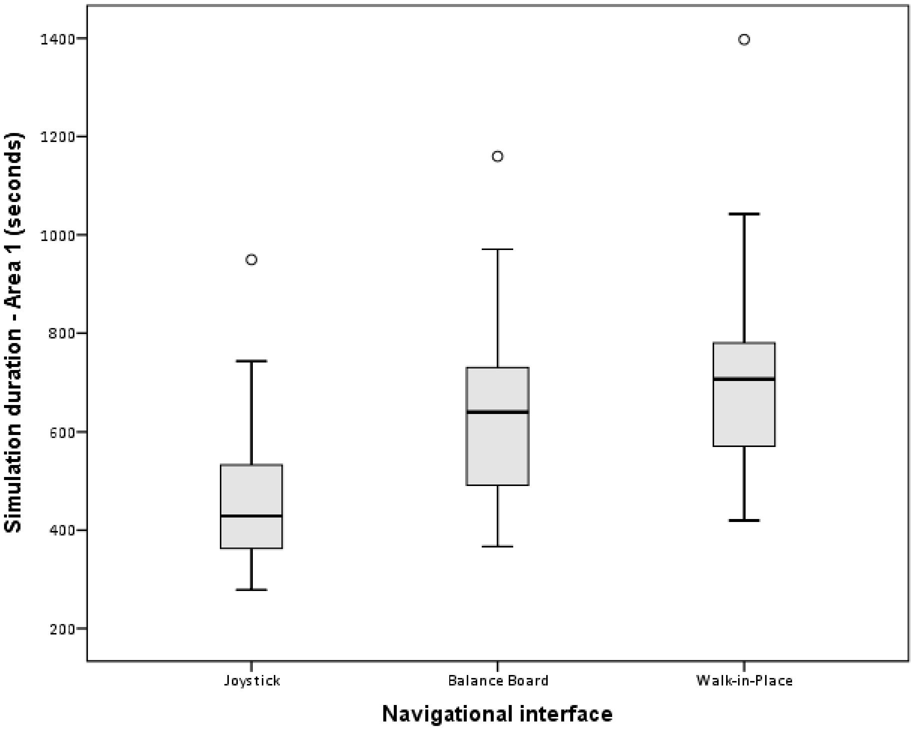


Figure 39 - Boxplots of the duration of the simulation in Area 1 - Rooms, by experimental condition

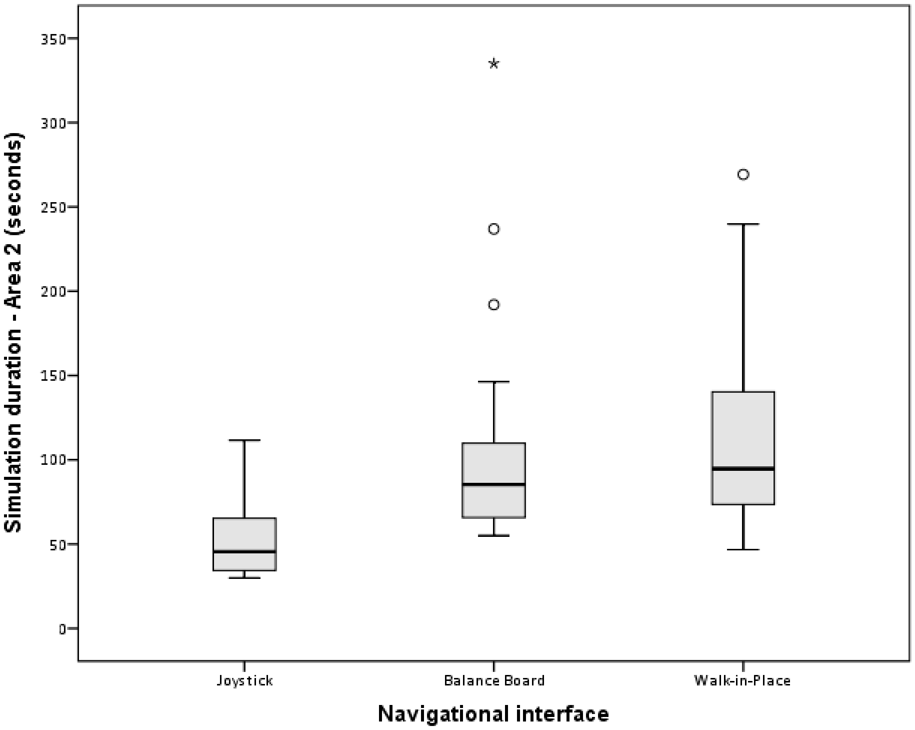


Figure 40 - Boxplots of the duration of the simulation in Area 2 - Escape Routes, by experimental condition

To verify if statistically significant differences were found, for the duration of the simulation, the Kruskal-Wallis test was performed and significant differences were found in *Area 1 – Rooms* ($\chi^2(2, 90) = 28.97$, $p < 0.001$) and in *Area 2 – Escape Routes* ($\chi^2(2, 90) = 34.77$, $p < 0.001$). The pairwise comparisons (with Dunn-Bonferroni correction) showed that statistically significant differences exist between the Joystick (with lower values) and the other navigational interfaces in all areas (*Area 1 – Rooms*: Balance Board: $p < 0.001$, Walk-in-Place: $p < 0.001$; *Area 2 – Escape Routes*: Balance Board: $p < 0.001$, Walk-in-Place: $p < 0.001$). No statistically significant differences were found for the pair Balance Board/Walk-in-Place in both areas.

As expected, the participants that used the Joystick had lower simulation durations than the participants that used the other two interfaces. This might be due to the more fine grained nature of control that is possible to have with an interface such as the Joystick, since the movement is controlled by the hand. The other navigational interfaces use the lower body as a form of control which does not have the same level of fine grained control. This limitation on fine grained control can cause participants to have certain difficulties or delays when trying to perform a locomotion-related action. When using the Joystick it is easier to initiate or make small corrections to movement since the amplitude of movement is smaller than with the other interfaces used in this study. For example, to initiate movement with the Balance Board, the participants need to shift enough of their weight in order to get out of the no movement area (i.e., dead zone in the interface to allow participants to keep still in the VE while standing). This movement is longer and requires more effort than doing the equivalent movement with the Joystick. Similarly, with the Walk-in-Place interface, the time that is required to initiate movement is usually longer than with the other interfaces, since it only starts the movement after the participants start raising their leg. In terms of changing directions, even though the response of the Walk-in-Place system is fast, since it requires the person to physically rotate to the direction they want to move, it can take longer than with the Joystick and the Balance Board. However, the angle precision that the person wants to move is easier to control with the Walk-in-Place than with the other two interfaces. Although not measured in this study, another possibility for higher values of duration for the interfaces that are controlled by the lower body, would be the tiredness that could happen during the simulation, decreasing the quickness that participants could make the desired movements.

b) Distance

On Table 12, the descriptive statistics are presented per area and for each one of the Navigational Interfaces. It is clear that, for the *Distance* variable (presented in meters), the Walk-in-Place has the lowest values, followed by the Joystick and the Balance Board in all areas.

Table 12 - Descriptive statistics for the *Distance* variable, in the different areas (in meters)

		Mean	**SD**	**Minimum**	**Maximum**
Area 1 - Rooms	*J*	318.29	111.6	172.59	660.35
	BB	362.46	153.04	202.43	999.28
	WiP	247.08	52.89	127.2	358.52
Area 2 - Escape Routes	*J*	73.92	21.64	52.95	119.38
	BB	90.15	46.15	41.01	297.09
	WiP	69.03	21.36	53.33	142.23

Note: J – Joystick, BB – Balance Board, WiP – Walk-in-Place

On Figure 41 and Figure 42 it is possible to observe that the variability of results with the Walk-in-Place interface has a lower range than with the other interfaces, which is more noticeable in *Area 1 – Rooms*.

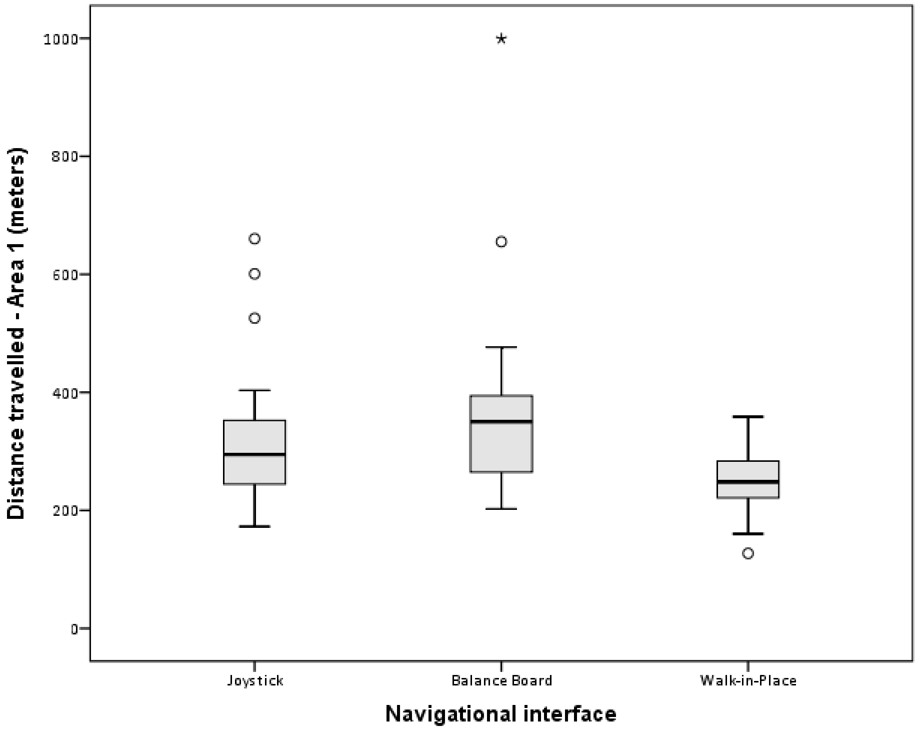


Figure 41 - Boxplots of the distance travelled in the simulation in Area 1 - Rooms, by experimental condition

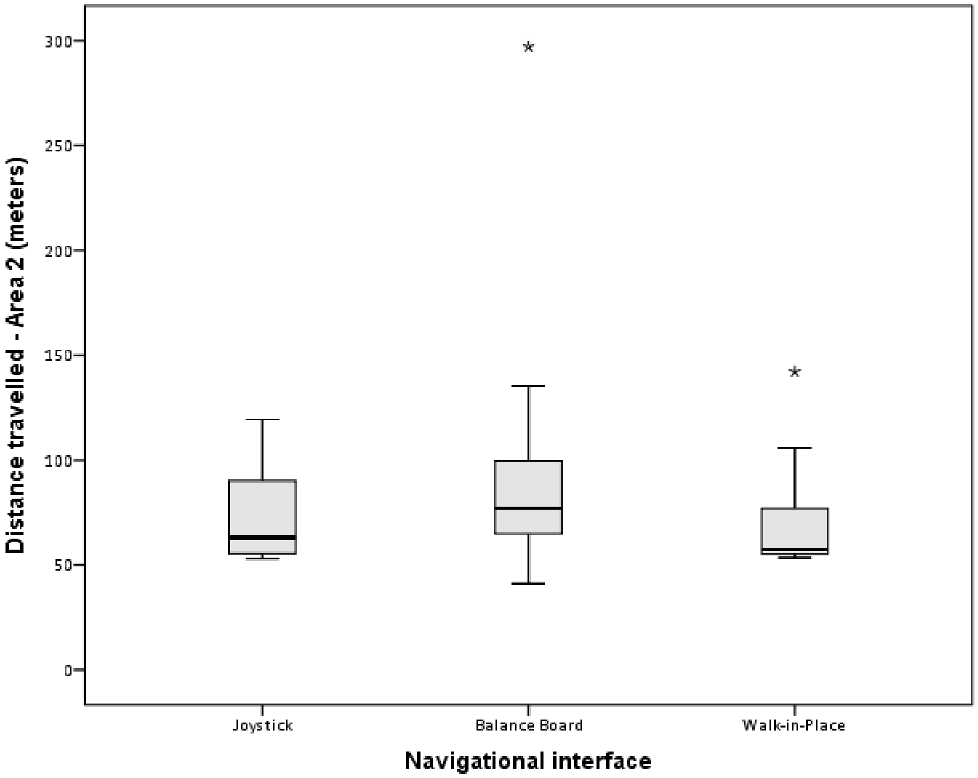


Figure 42 - Boxplots of the distance travelled in the simulation in Area 2 - Escape Routes, by experimental condition

To verify if statistically significant differences were found, for the distance travelled in the simulation, the Kruskal-Wallis test was performed and statistically significant differences were found in *Area 1 – Rooms* ($\chi^2(2, 90) = 19.93$, $p < 0.001$) and in *Area 2 – Escape Routes* ($\chi^2(2, 90) = 8.40$, $p = 0.015$). The pairwise comparisons (with Dunn-Bonferroni correction) showed that for *Area 1 – Rooms*, statistically significant differences exist between the Walk-in-Place (with lower values) and the other navigational interfaces (Joystick: $p = 0.011$, Balance Board: $p < 0.001$). For *Area 2 – Escape Routes*, statistically significant differences were found only for the Walk-in-Place/Balance Board pair ($p = 0.013$), with the Walk-in-Place having lower values.

As expected, the Walk-in-Place had lower values of *Distance* when compared with the other two navigational interfaces. This confirms what Riecke and colleagues (Riecke et al., 2010) mentioned in their study where participants had a navigational search task where they would control the rotations/translations either by physical motion or through a joystick. They observed that walking resulted in shorter navigation paths. The smaller values in *Distance* that were observed for the Walk-in-Place participants might also be due to different strategies of navigation because of the naturally higher level of energy consumption of this interface when compared with the Balance Board or the Joystick.

c) Pauses

Such as with the previous analysis, the pauses variables were considered in the two areas. The pauses were analyzed in number and duration. In terms of duration, the maximum and median durations for the pauses were analyzed. In this study, a *pause* was defined as the time interval, greater or equal to 2 seconds, during which the participant's virtual body was stationary in the VE.

Number of pauses

On Table 13, the descriptive statistics are presented per area and for each one of the Navigational Interfaces regarding the *Number of Pauses* variable. It is clear that the Joystick has the lowest values, followed by the Balance Board and the Walk-in-Place in both areas.

Table 13 - Descriptive statistics for the Number of pauses variable, in the different areas

		Mean	SD	Minimum	Maximum
Area 1 - Rooms	*J*	41.97	16.04	18	92
	BB	53.47	16.31	26	84
	WiP	66.40	23.61	34	156
Area 2 - Escape Routes	*J*	2.47	2.76	0	14
	BB	5.67	5.96	1	25
	WiP	9.27	5.91	1	24

Note: J – Joystick, BB – Balance Board, WiP – Walk-in-Place

The variability of the *Number of pauses* is larger and with higher mean values in the Walk-in-Place interface, as it can be seen in Figure 43 and Figure 44, for both areas.

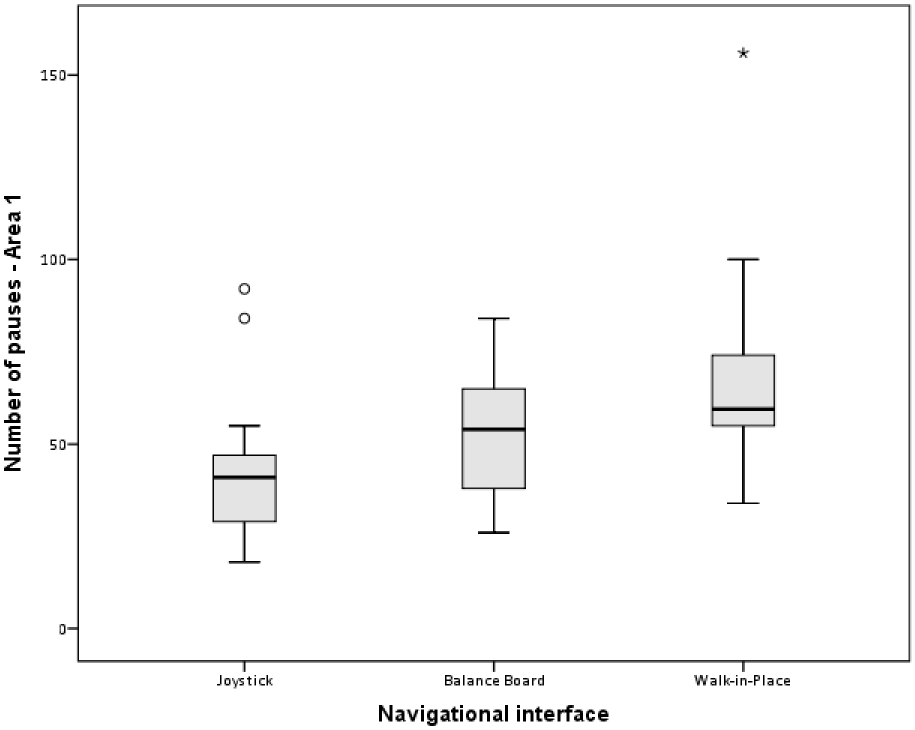


Figure 43 - Boxplots of the Number of pauses in Area 1 - Rooms, by experimental condition

To verify if statistically significant differences are present between the different navigational interfaces, Kruskal-Wallis tests were conducted and showed that statistically significant differences were found in *Area 1 – Rooms* ($\chi^2(2, 90) = 23.58$, $p < 0.001$) and in *Area 2 – Escape Routes* ($\chi^2(2, 90) = 30.64$, $p < 0.001$). The pairwise comparisons (with Dunn-Bonferroni correction) showed that for *Area 1 – Rooms*, statistically significant differences exist between the Joystick (with lower values) and the other navigational interfaces (Balance Board: $p = 0.018$, Walk-in-Place: $p < 0.001$). For *Area 2 – Escape Routes*, statistically significant differences were found for all pairs: Joystick/Balance Board ($p = 0.016$), Joystick/Walk-in-Place ($p < 0.001$) and Balance Board/Walk-in-Place ($p = 0.018$), with the Joystick having lower values and the Walk-in-Place having the highest values.

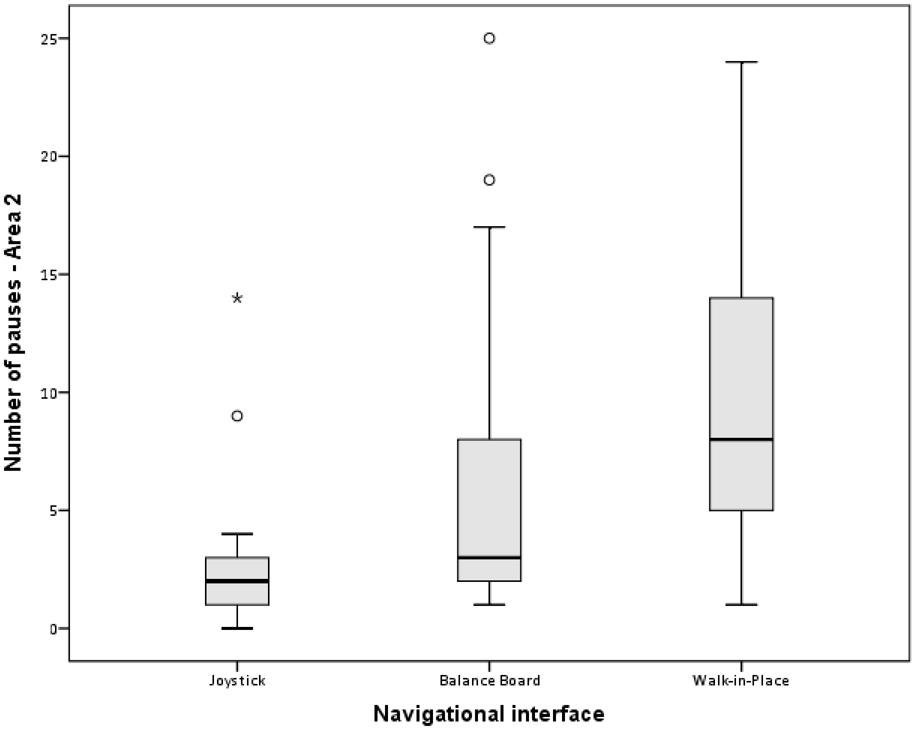


Figure 44 - Boxplots of the Number of pauses in Area 2 - Escape Routes, by experimental condition

Regarding the *Number of Pauses*, the results can be caused by the energy consumption associated with each navigational interface, the natural energy consumption management that people do when on a physical activity or muscular fatigue. Since the Joystick is probably the interface that requires less energy to control, the number of pauses with this interface are less than with the other navigational interfaces which is most likely related to the task at hand (e.g., reading signs, pressing the buttons) rather than a rest pause. The number of pauses can also be related with an intrinsic higher level of difficulty in controlling the navigational interface, especially for the Balance Board and the Walk-in-Place. Another possibility could be that since the Walk-in-Place requires more energy consumption, participants might risk less in their decisions and for that paying more attention to the environment, resulting in a higher level of visual exploration of the environment. An analysis of the location of these pauses as well as a detailed analysis of the observation patterns of participants could be enlightening in a future study.

Maximum duration of pauses

On Table 14, the descriptive statistics are presented per area and for each one of the Navigational Interfaces regarding the *Maximum duration of Pauses* variable (in seconds). The Joystick presents the lowest values, followed by the Balance Board and the Walk-in-Place in all areas. These results show that besides having a lower *Number of pauses* (presented earlier in Table 14), the *Maximum duration* of those pauses (on average) is also lower.

Table 14 - Descriptive statistics for the Maximum duration of pauses in the different areas

		Mean	SD	Minimum	Maximum
Area 1 - Rooms	*J*	17.6	6.49	8.18	33.95
	BB	23.54	12.71	10.48	81.31
	WiP	31.85	13.19	13.54	69.80
Area 2 - Escape Routes	*J*	5.38	2.14	2.34	10.98
	BB	6.74	5.48	2.25	26.46
	WiP	6.89	4.9	2.31	21.78

Note: J – Joystick, BB – Balance Board, WiP – Walk-in-Place

By observation of Figure 45 and Figure 46, it is possible to see that the variation of results with the Walk-in-Place interface is larger than with the other interfaces, especially in *Area 1 – Rooms*. This could be caused by the nature of the task at hand (since less or no pauses were expected to happen in *Area 2 – Escape Routes*), an increased difficulty in accomplishing a certain task with the Walk-in-Place interface or even to rest. For example, if a participant using the Walk-in-Place interface wants to read a directional sign while walking, it might not be easy to do so. This is because the participant, while doing the walk in place movement, naturally makes movements with the head, which moves the head sensor, creating therefore some image instability. In the real world, when we visually examine an object or walk towards it, it is perceived as a stationary structure despite the jerky translations, shearing motions or pulsatile expansions that take place in its retinal image (MacKay, 1973). However, in a VR system, when considering that the image presented is being moved according to a head sensor, that situation does not occur, creating therefore image instability. In a future study, the introduction of more sophisticated image stability filters due to motion should be implemented and analyzed if there are differences in the pauses.

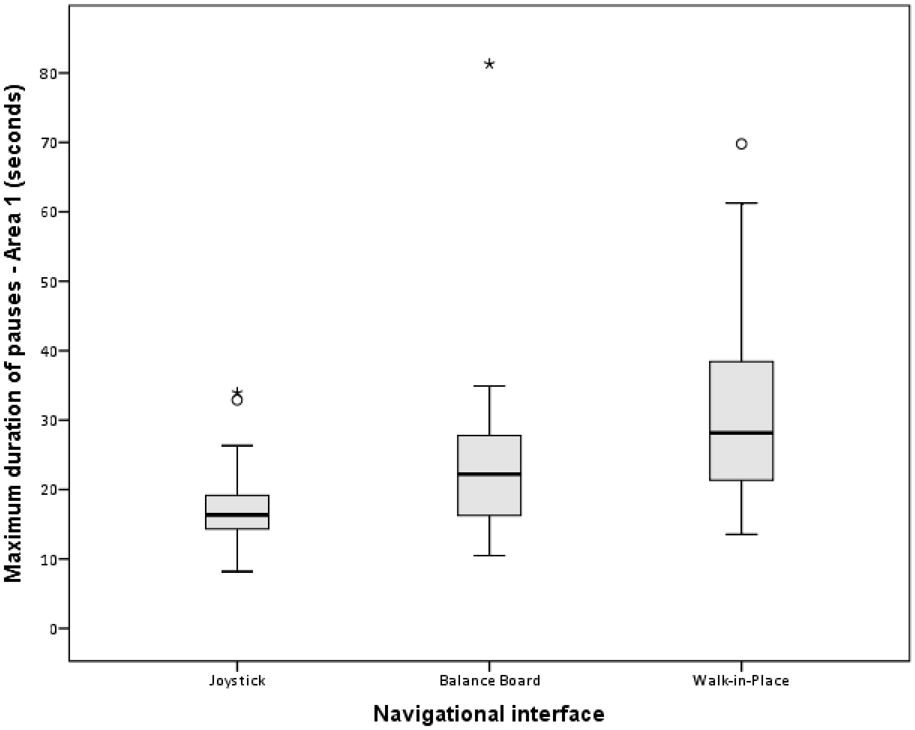


Figure 45 - Boxplots for the Maximum duration of the pauses in Area 1, for the different Navigational interfaces

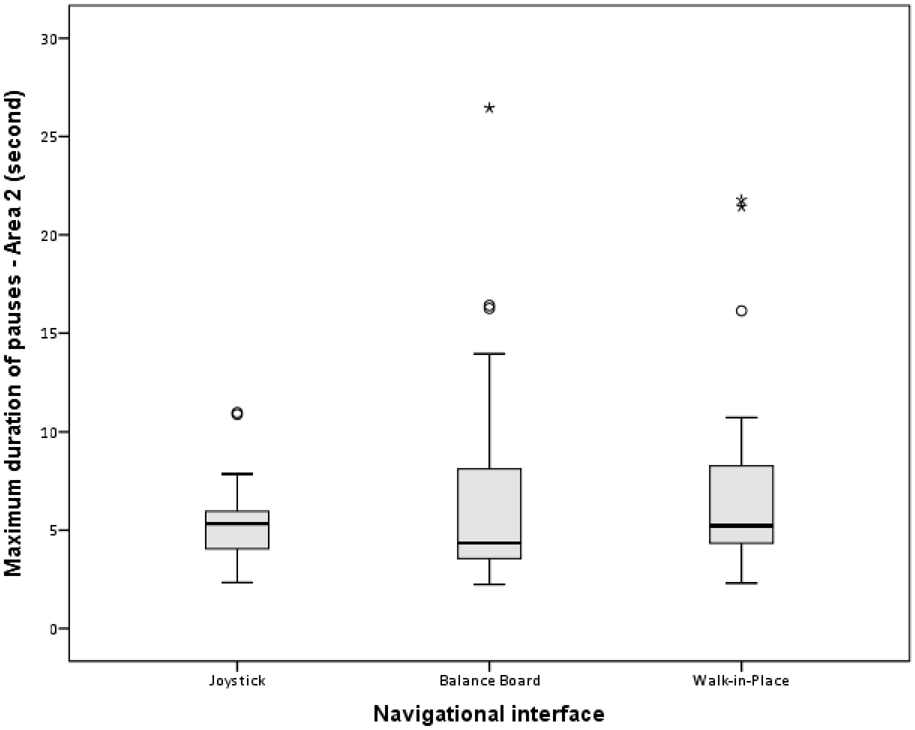


Figure 46 - Boxplots for the Maximum duration of the pauses in Area 2, for the different Navigational interfaces

For the maximum duration of the pauses, the non-parametric Kruskal-Wallis test was conducted and showed that statistically significant differences were found in *Area 1 – Rooms* ($\chi^2(2, 90) = 25.63$, $p < 0.001$) and no statistical significant differences were found in *Area 2 – Escape Routes* ($\chi^2(2, 89) = 0.909$, $p = 0.635$). The pairwise comparison (with Dunn-Bonferroni correction) showed that for *Area 1 – Rooms*, statistically significant differences exist between the Walk-in-Place and the other navigational interfaces, with the Walk-in-Place having longer pauses than the other navigational interfaces (Joystick: $p < 0.001$, Balance Board: $p = 0.013$).

Regarding the *Maximum duration of pauses*, the Walk-in-Place has a wider range of values, which could be an indication that the pauses and maximum duration of pauses are more dependent on how each participant completes the task rather than being caused by the navigational interface. Also, and since the Walk-in-Place is the interface that is closer to the natural movement, participants would need to manage the effort to save energy during the simulation, making therefore more and longer pauses outside the purview of the task at hand. A different methodology would be required to evaluate the energy consumption of participants during the simulation.

Median duration of pauses

On Table 15, the descriptive statistics regarding the *Median duration of pauses* (presented in seconds) are presented per area and for each one of the Navigational Interfaces. The Walk-in-Place has the highest values in *Area 1 – Rooms*, followed by the Joystick and the Balance Board and in *Area 2 – Escape Routes* the Walk-in-Place has the lowest values followed by the Balance Board and the Joystick.

Table 15 - Descriptive statistics for the Median duration of pauses in the different areas

		Mean	SD	Minimum	Maximum
Area 1 - Rooms	*J*	4.26	0.78	3.06	6.05
	BB	4.06	0.72	2.78	6.24
	WiP	4.78	0.87	3.37	7.36
Area 2 - Escape Routes	*J*	4.45	1.85	2.34	10.89
	BB	3.47	1.34	2.15	7.83
	WiP	3.28	0.84	2.18	4.82

Note: J – Joystick, BB – Balance Board, WiP – Walk-in-Place

By observing Figure 47 and Figure 48 it is possible to observe that the variability of results with the Walk-in-Place interface has a slightly lower range than with the other interfaces, in *Area 1 – Rooms* but with a higher median value. However, for *Area 2 – Escape Routes*, the

Joystick is the navigational interface that presents a higher range of values and with a higher median value followed by the Walk-in-Place and then the Balance Board.

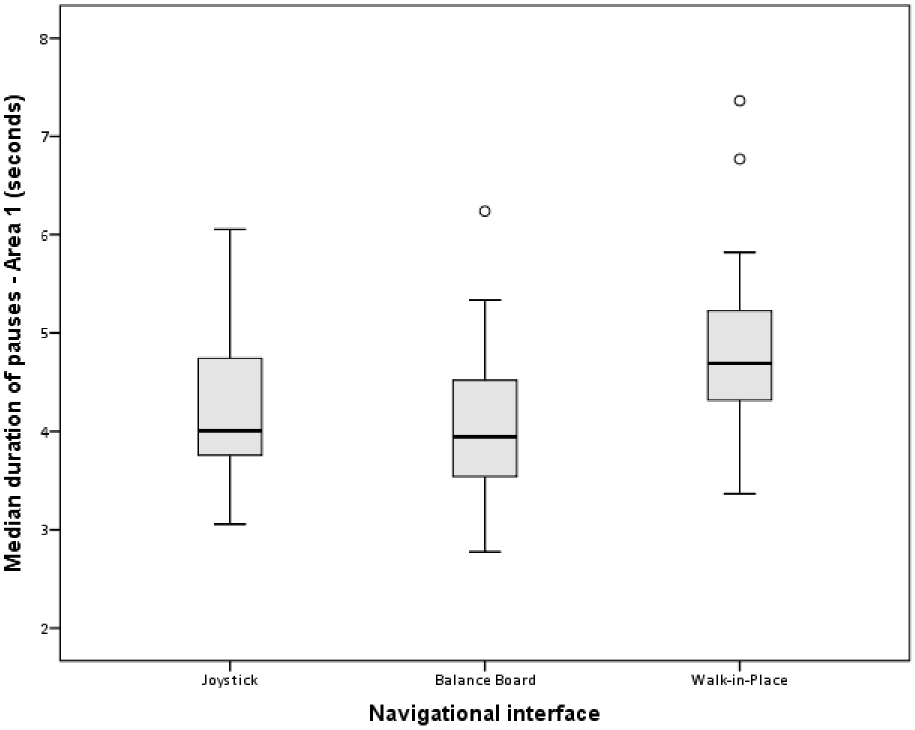


Figure 47 - Boxplots for the Median duration of the pauses in Area 1, for the different Navigational interfaces

For the Median duration of the pauses, Kruskal-Wallis tests showed that statistically significant differences were found in *Area 1 – Rooms* ($\chi^2(2, 90) = 13.01$, $p = 0.001$) and also in *Area 2 – Escape Routes* ($\chi^2(2, 89) = 10.64$, $p = 0.005$). The pairwise comparisons (with Dunn-Bonferroni correction) showed that for *Area 1 – Rooms*, statistically significant differences exist between the Walk-in-Place and the other navigational interfaces (Joystick: $p = 0.029$, Balance Board: $p = 0.002$). For *Area 2 – Escape Routes*, statistically significant differences were found between the Joystick and the other navigational interfaces (Balance Board: $p = 0.016$, Walk-in-Place: $p = 0.012$).

Since the *Number of Pauses* in *Area 2 – Escape Routes* were smaller with the Joystick than with the other interfaces, a Spearman correlation was made to evaluate if there is a relationship between the *Number of pauses* and the *Median duration of the pauses* to justify the difference found with the Joystick having higher values for the *Median duration of the pauses* in *Area 2 – Escape Routes*. There is a strong correlation in *Area 1 – Rooms* for the Walk-in-Place interface, in which when the *Number of pauses* increases, the value of the *Median duration of the pauses* decreases ($r = -0.481$, $p = 0.007$). No other correlations were found for either navigational interface or area.

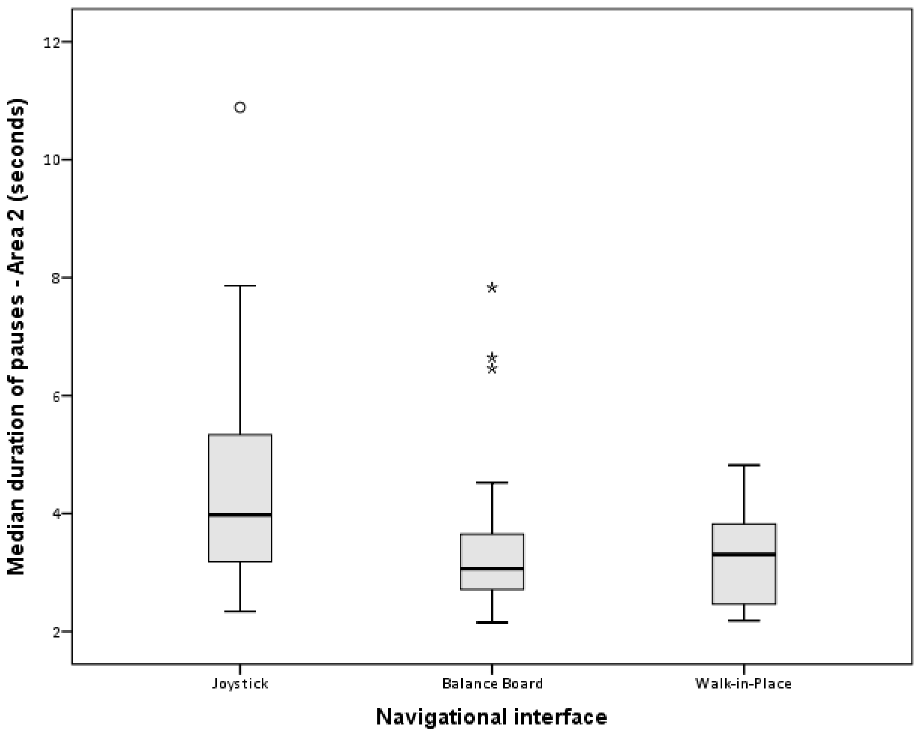


Figure 48 - Boxplots for the Median duration of the pauses in Area 2, for the different navigational interfaces

Regarding the *Median duration of pauses*, and taking into consideration the higher number of pauses and their maximum duration made by participants that used the Walk-in-Place, it was expected that the *median duration of the pauses* would be higher with the Walk-in-Place interface. That was confirmed for *Area 1 – Rooms.* However, for *Area 2 – Escape Routes*, the *median duration of the pauses* values, presented higher values with statistically significant differences with the Joystick having higher values when comparing to the other interfaces. This might be due to the reduced amount of pauses in all the navigational interfaces for *Area 2 – Escape Routes* but also, especially for the Joystick, because of the small number of pauses. A smaller amount of pauses with higher values, would result in a higher median value.

d) Average speed

On Table 16, the descriptive statistics regarding the *Average speed* (presented in meters per second) are presented per area and for each one of the Navigational Interfaces. For the *Average speed*, the Walk-in-Place has the lowest values in both areas, followed by the Balance Board and the Joystick. As mentioned before, *Average speed* was considered after removing the pauses durations from the total simulation time.

Table 16 - Descriptive statistics (presented in meters per second) for the Average speed in the different areas

		Mean	SD	Minimum	Maximum
Area 1 - Rooms	*J*	1.34	0.14	1.09	1.58
	BB	1.04	0.12	0.87	1.43
	WiP	0.89	0.14	0.60	1.12
Area 2 - Escape Routes	*J*	1.78	0.20	1.20	2.11
	BB	1.14	0.14	0.88	1.47
	WiP	0.94	0.18	0.56	1.25

Note: J – Joystick, BB – Balance Board, WiP – Walk-in-Place

The variability of the results with the Balance Board interface is presented by a slightly lower range than with the other interfaces, in both areas, as it can be observed in Figure 49 and Figure 50. Also, for either area, the Joystick has higher values than the other interfaces.

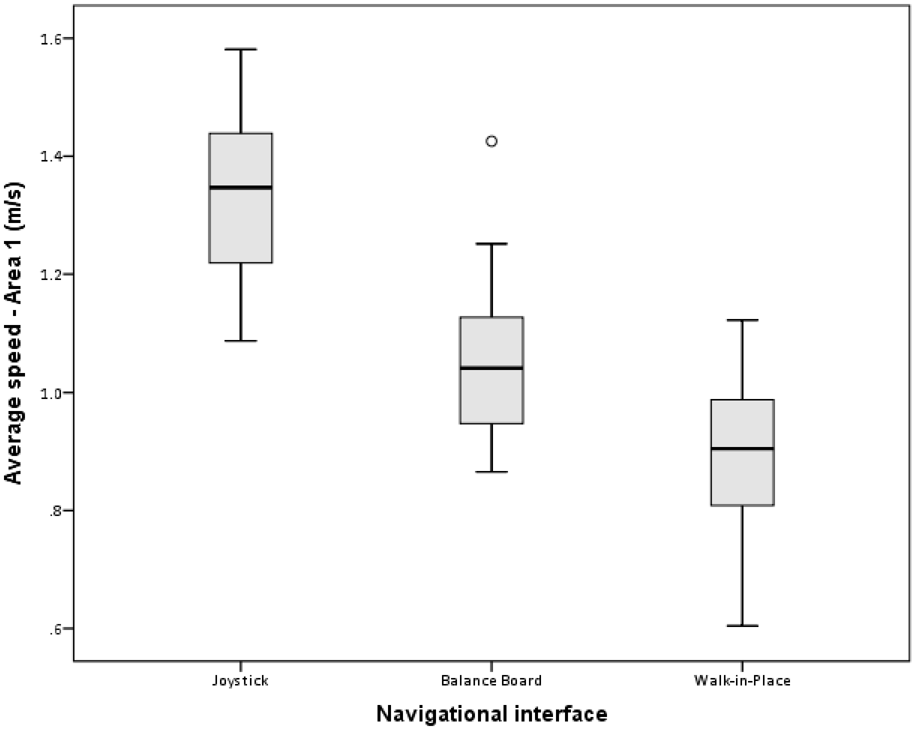


Figure 49 - Boxplots for the Average speed in Area 1, for the different Navigational interfaces

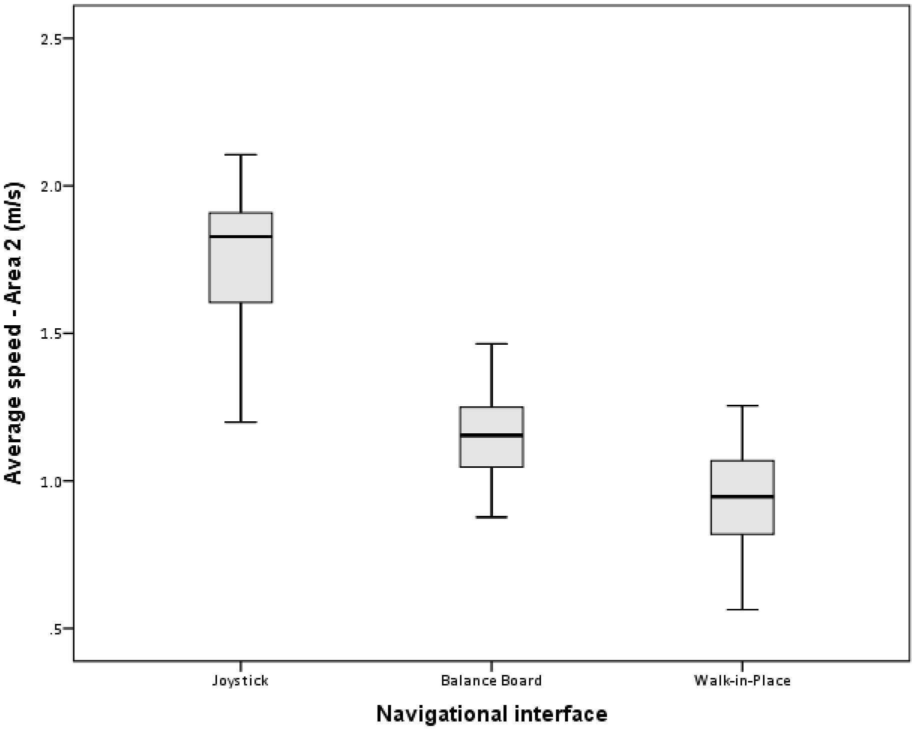


Figure 50 - Boxplots for the Average speed in Area 2, for the different Navigational interfaces

A two-way mixed ANOVA was made for the performance variable *Average Speed*, with the within-subject factor being the area (i.e., *Area 1 – Rooms* and *Area 2 – Escape Routes*) and the between-subjects factor being the navigational interface (i.e., *Joystick*, *Balance Board* and *Walk-in-Place*). The parametric approach was possible since the two-way ANOVA assumptions were met.

Regarding the *Average speed* variable, when considering the within-subjects effect, there is a significant interaction effect between the *area* and the *navigational interface* (F(2, 87) = 40.996, $p < 0.001$; $\eta_p^2 = 0.485$). There is also a significant difference of the average speed between the different areas (F(1, 87) = 101.484, $p < 0.001$; $\eta_p^2 = 0.538$). When considering the between-subjects factor, there is a significant effect of the *navigational interface* (F(2, 87) = 212.402, $p < 0.001$; $\eta_p^2 = 0.830$). The average and standard deviation for the interaction effect as well as the marginal values are presented in Table 17.

Table 17 - Two-way mixed ANOVA average (and standard deviation) for the interaction between the navigational interface and the area

	Area 1 – Rooms	***Area 2 – Escape Routes***	***Total***
J	1.337 (0.1412)	1.781 (0.1979)	1.559 (0.1199)
BB	1.042 (0.1243)	1.142 (0.1406)	1.092 (0.1096)
WiP	0.894 (0.1363)	0.939 (0.1775)	0.916 (0.1427)
Total	1.091 (0.2281)	1.287 (0.3994)	

Note: J – Joystick, BB – Balance Board, WiP – Walk-in-Place

As it can be seen in Figure 51, there is a noticeable difference of Average Speed between the navigational interfaces, with higher values for participants that used the Joystick. Also, the difference from *Area 1 – Rooms* and *Area 2 – Escape Routes* is significant, especially for the Joystick. That difference is less noticeable with the Balance Board and even less with the Walk-in-Place. This shows that the Joystick has an ability to reach higher average speeds in tasks such as the one in *Area 2 – Escape Routes*. Although the increase of the average speed with the other two interfaces exists, the difference is not as noticeable as with the Joystick, which can mean that the Joystick is a navigational interface that allows participants to have a bigger range of average speed whereas with the Balance Board and the Walk-in-Place, the range is smaller.

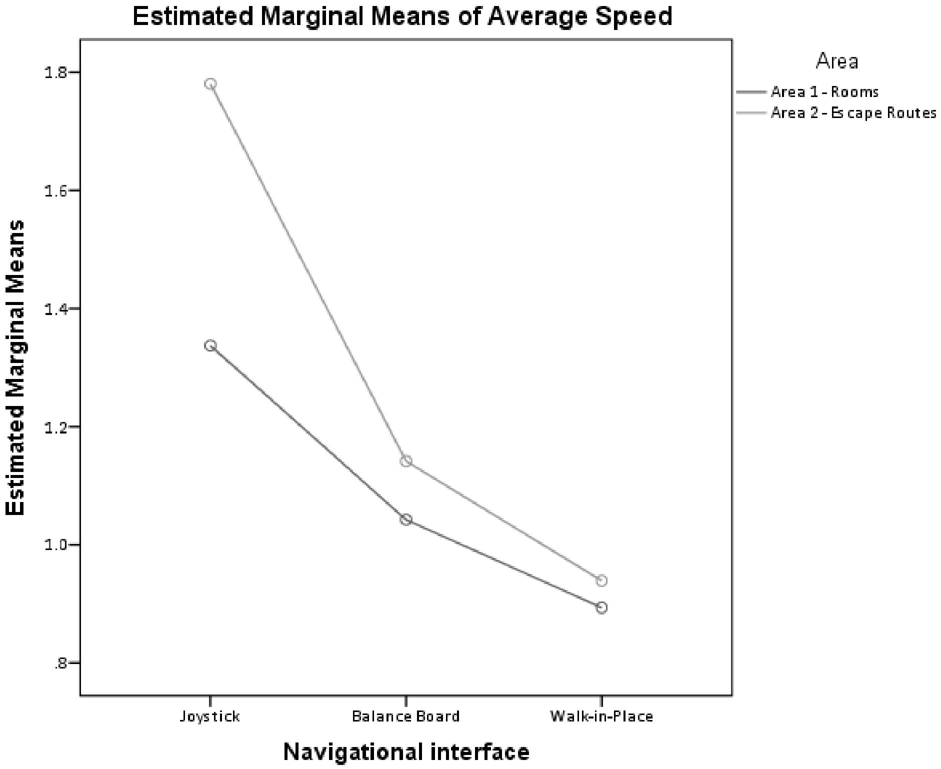


Figure 51 - Estimated Marginal Means of Average Speed

Due to the nature of the movement made with the Walk-in-Place, it was expected that participants that used this interface would have lower average speed values. For participants to be able to "run" with the Walk-in-Place interface they would need to make a faster movement, closer to running in the same place. Such movement would have a higher energy consumption than the normal Walk-in-Place movement and participants would not be able to sustain this type of movement for long consecutive periods of time. With the other interfaces it is easier to keep a higher velocity for longer periods of time without such high levels of energy consumption. With the Joystick it is only required to thrust the joystick handle further and the dislocation speed will increase. With the Balance Board, participants had to shift their weight forward (by leaning over the platform), which although requiring more energy than with the Joystick it is significantly less than with the "running" in the same place that would be required with the Walk-in-Place interface.

Results confirmed these assumptions where the Walk-in-Place had the lowest average speed values in both areas, followed by the Balance Board and finally the Joystick with the highest values. Also, the difference of the type of task asked to be performed in each area, was confirmed with statistically significant differences regarding the average speed found between the areas and also the main effect of the type of navigational interface used.

e) Gender differences

To evaluate if there were *Gender* differences on the performance variables, Mann-Whitney U tests with *Gender* as the grouping variable was conducted. No statistically significant differences were found for any of the performance variables for any of the areas: *duration* (*Area 1 – Rooms*: U = 847, W = 1882, *p* = 0.182; *Area 2 – Escape Routes*: U = 888, W = 1923, *p* = 0.315), *distance* (*Area 1 – Rooms*: U = 965, W = 2000, *p* = 0.701; *Area 2 – Escape Routes*: U = 942, W = 1977, *p* = 0.569), *number of pauses* (*Area 1 – Rooms*: U = 851, W = 1886, *p* = 0.191; *Area 2 – Escape Routes*: U = 900, W = 1935, *p* = 0.360), *maximum duration of pauses* (*Area 1 – Rooms*: U = 887, W = 1922, *p* = 0.309; *Area 2 – Escape Routes*: U = 909, W = 1899, *p* = 0.504), *median duration of pauses* (*Area 1 – Rooms*: U = 999, W = 2034, *p* = 0.910; *Area 2 – Escape Routes*: U = 781, W = 1771, *p* = 0.086) and for *average speed* (*Area 1 – Rooms*: U = 838, W = 1873, *p* = 0.159; *Area 2 – Escape Routes*: U = 912, W = 1947, *p* = 0.417). This information can be seen in Table 18.

Table 18 - Summary of the Mann-Whitney test results regarding Gender differences for the performance variables

	Area 1 – Rooms			***Area 2 – Escape Routes***		
Variable	U	W	*p*	U	W	*p*
Duration	847	1882	0.182	888	1923	0.315
Distance	965	2000	0.701	942	1977	0.569
Number of pauses	851	1886	0.191	900	1935	0.360
Maximum duration of pauses	887	1922	0.309	909	1899	0.504
Median duration of pauses	999	2034	0.910	781	1771	0.086
Average speed	838	1873	0.159	912	1947	0.417

3.3.3 Sense of presence

Summary: *This topic reports the results from the analysis of the sense of presence variables. Those variables are* Quality of Sensorial Experience *(QSE),* Quality of Interaction *(QI),* Quality of Interaction for the Navigational Interface *(QINI),* Distraction Factors *(DF),* Realism Level *(RL),* Notion of time *(NT) and* Enjoyment *(ENJ). These variables were divided in a set of 22 questions that participants replied after the simulation. It was expected to see a positive difference for the sense of presence variables for participants that used the Walk-in-Place interface. However, and for the same reason, it was also expected to see a negative difference in terms of ENJ since it might not be as exciting as using another type of interface. The results show that statistically significant differences were only found in the RL variable. A Gender effect was found for the QI variable, with males having higher values.*

The *sense of presence* variables mentioned in this topic are *Quality of Sensorial Experience* (QSE), *Quality of Interaction* (QI), *Quality of Interaction for the Navigational Interface* (QINI), *Distraction Factors* (DF), *Realism Level* (RL), *Notion of time* (NT) and *Enjoyment* (ENJ). As mentioned before, these variables were part of the questionnaire presented to participants after the simulation ended, and the relevant questions were presented in Table 1 in page 73. The final scores were computed as the mean of the value of the 7-point Likert-scale of the answers for each group of questions. The most positive answers would be at the top of the scale for every variable except for *DF* where lower values are better. For each one of the abovementioned variables, it was verified if a *Gender* effect was present. In terms of expected results, it was expected to see a positive difference for the sense of presence variables for participants that used the Walk-in-Place interface.

By observing Table 19, it is possible to notice that the Joystick had the lowest mean scores for *Quality of Sensorial Experience*, *Quality of Interaction, Realism Level*, *Notion of Time* and *Enjoyment*. However, for the *Quality of Interaction for the Navigational Interface*, the Joystick had the highest scores, being followed by the Walk-in-Place and at last the Balance Board. Regarding the *Distraction Factors*, the Joystick had the highest scores (lower values are better), followed by the Balance Board and then the Walk-in-Place.

Table 19 - Descriptive statistics for the Sense of Presence variables

		Mean	**SD**	**Median**	**IQR**	**Min**	**Max**
Quality of Sensorial Experience	*J*	5.02	0.893	5.08	1.17	2.83	6.67
	BB	5.26	0.9	5.42	0.875	3	6.5
	WiP	5.19	0.84	5.5	0.708	2.33	6.67
Quality of Interaction	*J*	4.68	0.901	4.56	1.09	2.25	6.38
	BB	4.88	0.714	4.88	1.06	3.63	6.75
	WiP	4.99	0.871	5.13	1.28	2.5	6.25
Quality of Interaction for the Navigational Interface	*J*	4.74	0.995	4.75	1.31	2.5	6.5
	BB	4.39	0.89	4.25	1.25	3	7
	WiP	4.71	0.981	4.88	1	2	6.5
Distraction Factors*	*J*	2.79	1.06	2.63	1.63	1	5
	BB	2.81	0.918	2.63	1.31	1	4.75
	WiP	2.96	1.08	2.5	1.75	1.5	5.5
Realism Level	*J*	4.34	0.344	4.25	0.75	3.75	5
	BB	4.72	0.784	5	1.13	2.5	6
	WiP	4.6	0.865	4.5	1.13	3	6.5
Notion of Time	*J*	4.3	1.62	4	3	1	7
	BB	4.63	1.4	4.5	3	2	7
	WiP	4.33	1.73	5	2.25	1	7
Enjoyment	*J*	5.23	1.41	5	2.25	1	7
	BB	5.53	1.28	6	1	1	7
	WiP	5.37	1.4	6	2	1	7

*Note: J – Joystick, BB – Balance Board, WiP – Walk-in-Place, * (lower values are better)*

In terms of *Quality of Sensorial Experience*, it is possible to observe in Figure 52 that the Joystick had a higher variability of values and with a lower median than the other two navigational interfaces.

For the *Quality of Interaction* (see Figure 53), the Walk-in-Place interface has the higher variability of values. Although the maximum value of the Walk-in-Place is lower than with the other two interfaces, it has the highest median value. Regarding the *Quality of Interaction of the Navigational Interface*, the Balance Board has a range of values smaller than the other interfaces and close to the center of the scale (see Figure 54). *Distraction Factors* presents a range of values for the Walk-in-Place slightly higher (which means worse results for this variable) in the scale than the other two interfaces (although having a lower median value, as it is possible to see in Figure 55). The values for the Joystick, in terms of *Realism Level* (boxplot present in Figure 56), have a very narrow range, in the middle of the scale and having the lowest median value. Contrary to what was expected, the Walk-in-Place did not have the highest median value for the *Realism Level*. The values and respective range for each interface, for *Notion of Time* were quite similar (see Figure 57), but with different median values, with the Walk-in-Place having the highest values, followed by the Balance Board and the Joystick. Regarding *Enjoyment*, it is clear by observation of the boxplot in Figure 58, that the Balance Board had the highest values and with less variation in range of responses.

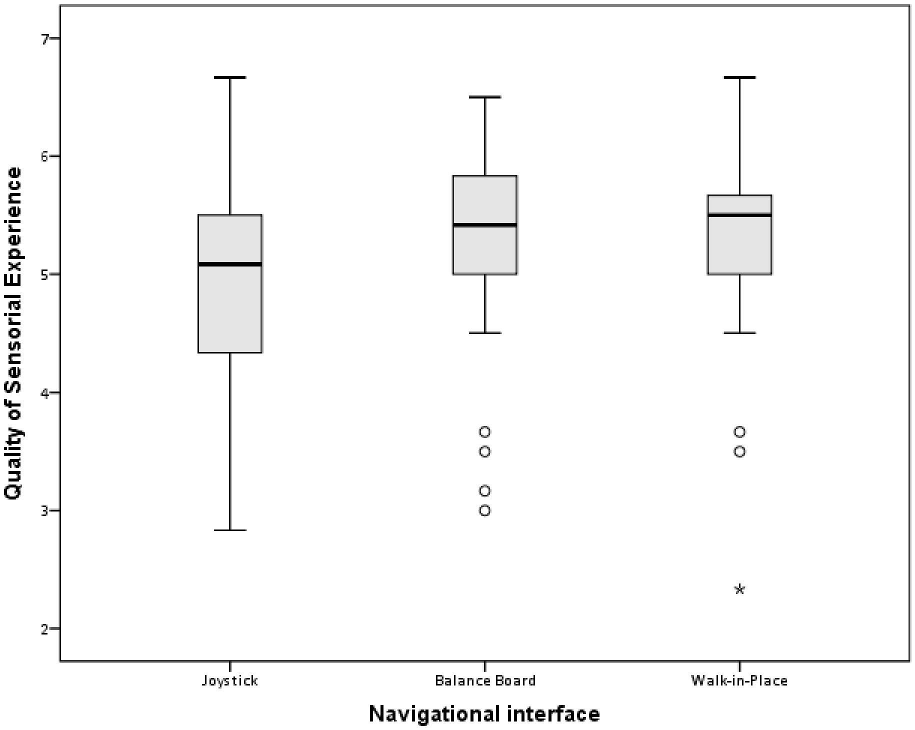


Figure 52 - Boxplots for the Quality of Sensorial Experience for each of the Navigational Interfaces

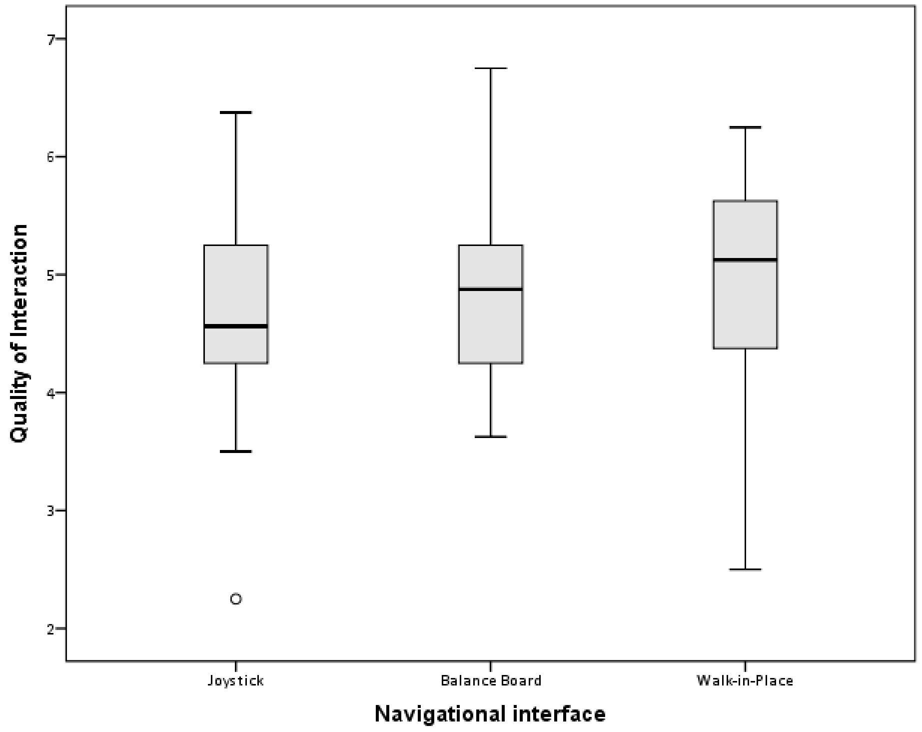


Figure 53 - Boxplots for the Quality of Interaction for each of the Navigational Interfaces

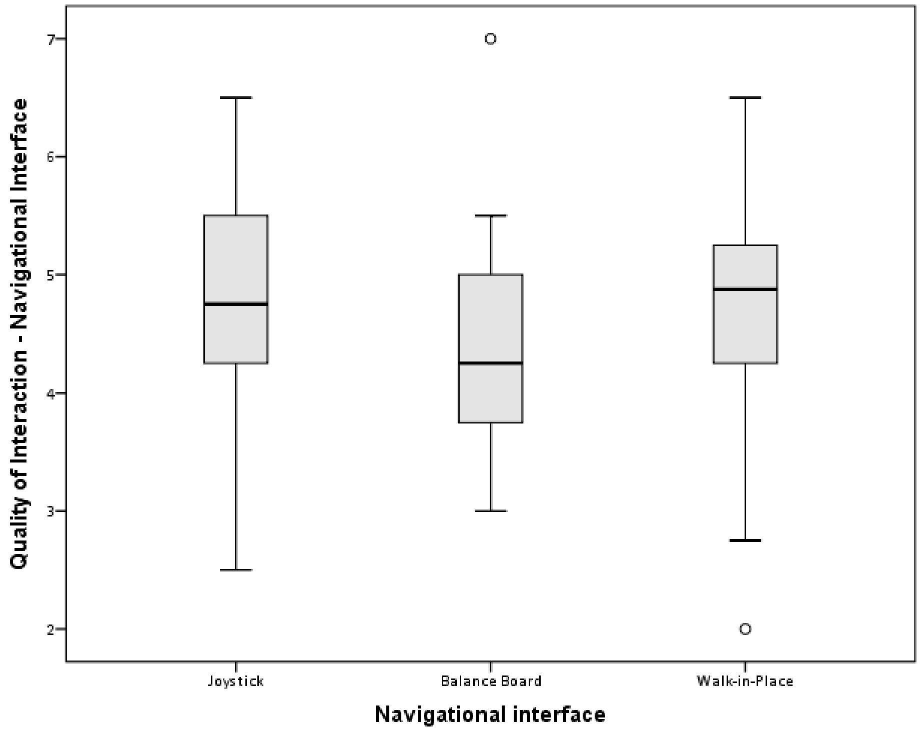


Figure 54 - Boxplots for the Quality of Interaction for the Navigational Interface for each of the Navigational Interfaces

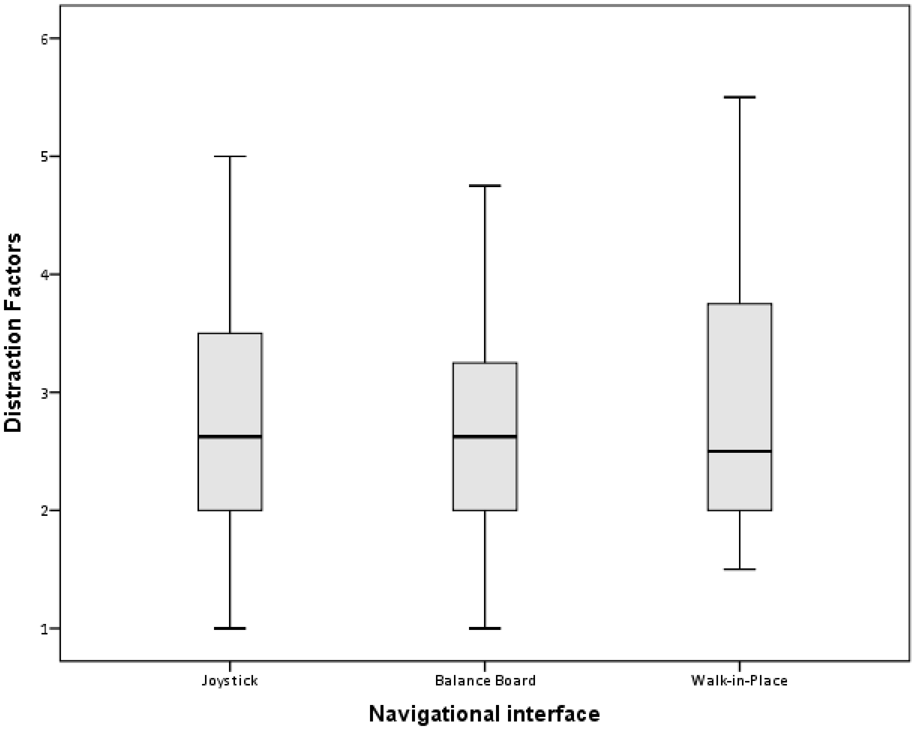


Figure 55 - Boxplots for the Distraction Factors for each of the Navigational Interfaces

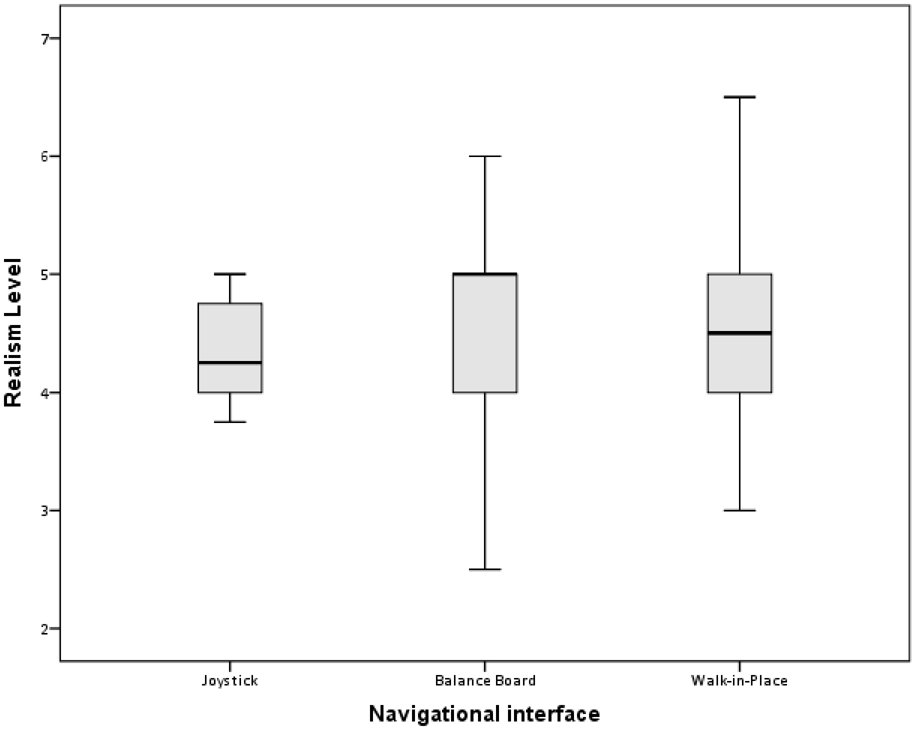


Figure 56 - Boxplots for the Realism Level for each of the Navigational Interfaces

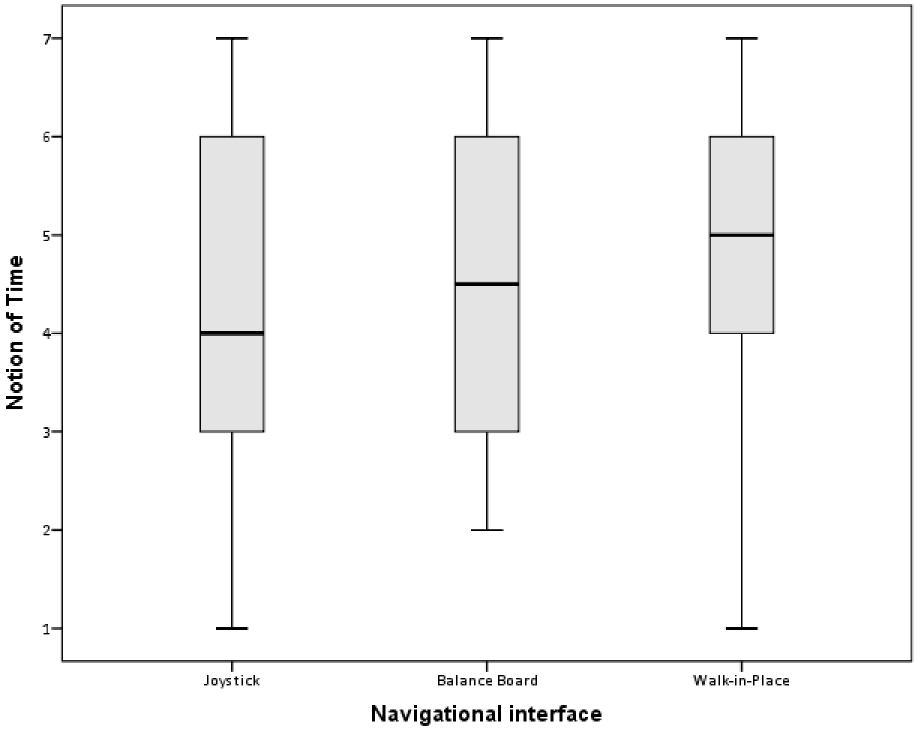


Figure 57 - Boxplots for the Notion of Time for each of the Navigational Interfaces

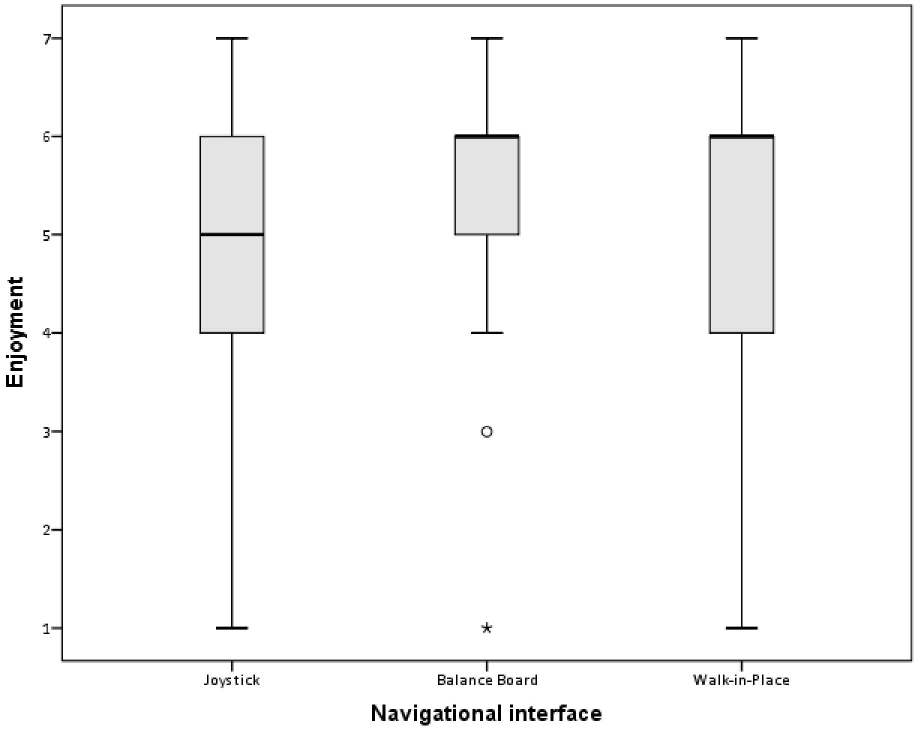


Figure 58 - Boxplots for the Enjoyment for each of the Navigational Interfaces

Due to the violation of normality assumptions, Kruskal-Wallis tests were conducted to compare the different navigational interfaces (i.e., *Joystick*, *Balance Board* and *Walk in Place* interfaces) concerning the sense of presence variables. The test showed that statistically significant differences were only found for *RL* ($\chi^2(2, 90) = 6.79$, $p = 0.034$). The pairwise comparison between the navigational interfaces for the *RL* variable showed statistically significant differences for the pair Joystick/Balance Board ($p = 0.028$). No differences were found for the other pairs.

No statistically significant differences were found for *QSE* ($\chi^2(2, 90) = 3.08$, $p = 0.214$), *QI* ($\chi^2(2, 90) = 2.88$, $p = 0.237$), *QINI* ($\chi^2(2, 90) = 3.91$, $p = 0.142$), *DF* ($\chi^2(2, 89) = 0.306$, $p = 0.858$), *NT* ($\chi^2(2, 90) = 0.702$, $p = 0.704$) and *ENJ* ($\chi^2(2, 90) = 1.11$, $p = 0.575$).

Regarding the remaining variables, the Walk-in-Place interface shows a tendency for higher values, although that tendency is not statistically significant.

Furthermore, several Pearson's and Spearman's correlation coefficients were calculated, according to the type of variable of the sense of presence in the study. These correlations were made globally (see Table 20) and for each one of the navigational interfaces (see Table 21 for the Joystick, Table 22 for the Balance Board and Table 23 for the Walk-in-Place). A correlation is significant at the 0.05 level if *p* (2-tailed) < 0.05 and at the 0.01 level if *p* (2-tailed) < 0.01. The values of the correlation between the *QI* and *QINI* were ignored since *QINI* is a subset of *QI*. The values presented in the correlation tables for the *QI* and *QINI* variables are from Pearson's correlation (because both variables are normally distributed) and Spearman's correlations for the rest of the sense of presence variables.

Table 20 - Correlations found for the sense of presence variables, globally

	QSE	**QI**	**DF**	**RL**	**NT**	**ENJ**	**QINI**
QSE		0.583^{**}			0.264^{*}	0.342^{**}	0.445^{**}
QI	0.603^{**}		-0.309^{**}			0.245^{*}	
DF		-0.282^{**}			-0.238^{*}		-0.294^{*}
RL							
NT						0.318^{**}	
ENJ		0.219^{*}					
QINI	0.512^{**}		-0.295^{*}				

**** correlation is significant at the 0.05 level (2-tailed)***

***** correlation is significant at the 0.01 level (2-tailed)***

By observing Table 20 it is possible to notice that there is a large positive correlation (Cohen, 1988)[15] between QSE and QI and also between QINI and QSE. A medium positive correlation was found between QSE and ENJ, between QSE and QINI, QI and ENJ, NT and ENJ and a medium negative correlation between QINI and DF. A small positive correlation was found between QSE and NT and between ENJ and QI. DF affects negatively the QI, NT and QINI as it can be seen with the small negative correlation between those variables.

It is of note the negative correlations with DF that were found when analyzing globally. The values of DF get lower when the QI, ENJ and QINI values get higher. When interacting with the VR system, if participants find some difficulties with the interaction devices, they will feel less present in the VE, more distracted with other elements than the simulation and as a consequence they would not enjoy the experience as much. It is also possible to observe that the QSE has a correlation with the NT and ENJ, making it a strong indication that the more immersed participants are in the VE, the more participants lose the notion of time and making it a more enjoyable experience.

Regarding the correlations when considering only the Joystick (presented in Table 21), there is a large positive correlation between QSE and QI and between QSE and QINI. A medium positive correlation was found between QSE and ENJ and between QI and ENJ. A medium negative correlation was found between DF and QINI. Similarly to what was observed in the global results, the lower the value of QINI, the greater are the DF. However, QINI is the only variable that affects the DF.

Table 21 - Correlations found for the sense of presence variables, for the Joystick

	QSE	**QI**	**DF**	**RL**	**NT**	**ENJ**	**QINI**
QSE		0.584^{**}				0.429^{*}	0.516^{**}
QI	0.721^{**}					0.421^{*}	
DF							-0.439^{*}
RL							
NT							
ENJ							
QINI	0.565^{**}		-0.409^{*}				

**** correlation is significant at the 0.05 level (2-tailed)***

***** correlation is significant at the 0.01 level (2-tailed)***

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[15] According to Cohen's (1988) guidelines, a correlation coefficient's size can be interpreted as follows: "small" – negative: -0.3 to -0.1 / positive: 0.1 to 0.3; "medium" – negative: -0.5 to -0.3 / positive: 0.3 to 0.5; "large" – negative: -1.0 to -0.5 / positive: 0.5 to 1.0.

Regarding the correlations when considering only the Balance Board (presented in Table 22), there are only large positive correlations and they were found between QSE and QI and between QSE and QINI.

Table 22 - Correlations found for the sense of presence variables, for the Balance Board

	QSE	**QI**	**DF**	**RL**	**NT**	**ENJ**	**QINI**
QSE		0.699**					0.603**
QI	0.583**						
DF							
RL							
NT							
ENJ							
QINI	0.588**						

**** correlation is significant at the 0.05 level (2-tailed)***

***** correlation is significant at the 0.01 level (2-tailed)***

Regarding the correlations when considering only the Walk-in-Place (presented in Table 23), it was found a large positive correlation between NT and ENJ. A large negative correlation was found between QI and DF. A medium positive correlation was found between QI and QSE and between QINI and QSE. A medium negative correlation was found between DF and QI, DF and ENJ, and between DF and QINI. The DF correlation with QI, ENJ and QINI that was observed to the global results are concentrated in the Walk-in-Place interface. This could be due to various factors but one that might had a stronger influence were the cabling of the HMD and the head sensor that in certain occasions could interfere negatively with the participants, bothering them if the cables would get tangled after several complete turns into the same direction.

Table 23 - Correlations found for the sense of presence variables, for the Walk-in-Place

	QSE	QI	DF	RL	NT	ENJ	QINI
QSE							
QI	0.494^{**}		-0.587^{**}				
DF		-0.543^{**}				-0.493^{**}	-0.476^{**}
RL							
NT						0.530^{**}	
ENJ							
QINI	0.462^{*}		-0.486^{**}				

**** correlation is significant at the 0.05 level (2-tailed)***

***** correlation is significant at the 0.01 level (2-tailed)***

Regarding the variables of the *Sense of presence*, only the *Realism Level* presented statistically significant differences and only between the pair Joystick/Balance Board. Since the questions were related to the global experience, the results could mean that the navigational interface did not play as an important role as other elements in the simulation.

a) Gender differences

To evaluate if there were any *Gender* differences on the *sense of presence* variables, a non-parametric Mann-Whitney U test with *Gender* as the grouping variable was made. *Gender* does not have a statistically significant effect on the *sense of presence* variables *QSE* (U = 966.5, W = 2001.5, p = 0.712), *QINI* (U = 860, W = 1895, p = 0.219), *DF* (U = 803, W = 1838, p = 0.124), *RL* (U = 937.5, W = 1972.5, p = 0.544), *NT* (U = 973.5, W = 2008.5, p = 0.750), *ENJ* (U = 939, W = 1974, p = 0.543).

Gender differences were found globally for the *QI* variable (U = 729, W = 1764, p = 0.022). When analyzing per navigational interface, *Gender* differences were found only for the Joystick interface. In both situations, males selected higher values for the *QI* variable.

3.3.4 Simulator sickness

Simulator sickness is a common condition experienced by VR users. A primary suspect on the cause of simulator sickness is inconsistent information about body orientation and motion received by the different senses, known as the cue conflict theory (Kolasinski, 1995). Usually this is due to the VR system giving information to a specific sense and the remaining senses are not stimulated in the same way. For example, the visual system receives information that the body is moving while the vestibular system perceives that the body is stationary. More details on simulation sickness, its causes and effects can be found in (Cobb et al., 1999; Golding, 2006; Kolasinski, 1995).

There are different levels of simulator sickness, from mild (which allows the participant to finish the simulation) to severe (which the simulation must be stopped). As such, for this study only participants that were able to finish the simulation were considered. Those that had to give up, due to simulator sickness or another reason, were excluded from the sample. As mentioned before, the data collection phase took place until it was possible to have 30 participants (equally divided in gender) for each experimental condition. As such, the data presented here are partial in that regard.

In Table 24 it is possible to see the number of participants, per experimental condition, that suffered from simulator sickness. Except for the Balance Board condition, the other results are between 5 and 10%. The higher values for the Balance Board could be explained by the extra movement that is required to shift the weight to move to the desired position. There is a higher tendency for females to suffer from simulator sickness, as a consequence of hormonal variations (Clemes & Howarth, 2005).

Table 24 - Simulator sickness descriptive statistics

Experimental condition	**Simulator sickness cases**			**Other problems**	**Total participants**	**Total valid**
	Male	Female	Total			
Joystick	1	2	3 (7%)	10 (23%)	43	30
Balance Board	3	4	7 (16.7%)	5 (12%)	42	30
Walk-in-Place	0	3	3 (8%)	5 (13%)	38	30
		Total	13 (10.6%)	20 (16.3%)	123	90

3.4 Conclusions

Regarding the studies of behavioral compliance with warnings and wayfinding that used the model described in this document, one question that remained open when they were developed was if the navigational interface used would affect the obtained results, i.e., if it would affect the observed behavior of participants. As such, and focusing on behavioral compliance with warnings first, a test was devised that would compare two navigational interfaces (Balance Board and Walk-in-Place) with the results obtained in the Static Uncluttered condition defined by Duarte (Duarte et al., 2013) with the Joystick.

The three experimental conditions (i.e., Joystick, Balance Board and Walk-in-Place), took place in an end-of-day routine security check scenario, where participants were asked to replace a coworker that got sick and follow written instructions left by that coworker in the environment.

The environment was comprised of two areas: *Area 1 – Rooms* and *Area 2 – Escape Routes*. *Area 1 – Rooms* is the area where the written instructions are presented and participants are confronted with the *uncued* and *cued* signs. *Area 1 – Rooms* is composed by four rooms, where in each an instruction and an action needed to be interpreted and performed. When participants entered the Warehouse (the last room in the sequence of events), a fire would start and participants needed to leave the building through *Area 2 – Escape Routes*. This area is composed by 6 t-shaped corridors and in each intersection, only one of the options would lead to the exit. An *exit sign* was present in each intersection directing participants to the correct path.

A total of 123 people participated in this study. Due to diverse events such as simulator sickness, equipment and energy malfunctions, external interruptions or the participants wanted to stop, only a group of 90 participants were part of the final sample, separated equally by number and gender through the 3 experimental conditions.

Behavioral compliance with warnings was measured for *Area 1 – Rooms* by the number of the buttons that participants pressed, either for the *cued signs* (warnings that were mentioned in the instructions that were posted throughout the environment) as for the uncued (that were not mentioned in the instructions). For *Area 2 – Escape Routes*, behavioral compliance was measured by the number of correct decisions made at the first try in each intersection (the correct choice is the direction to where the emergency exit sign pointed).

The results gathered for Behavioral compliance, are in accordance with Duarte's (2013) results, with no statistical significant differences found between the three navigational interfaces. This means that the navigational interfaces were not cumbersome to control and would allow navigating in the Virtual Environment with a minimum of ease, not affecting the completion of the task, or it might mean that the navigational interface does not affect the completion of the task. Consequently, neither one of the three navigational interfaces used in this study, affected the behavioral compliance of participants, as it was expected.

Another interesting result, although no statistical significant differences were found, is that for the *compliance with uncued signs* and the *compliance with exits signs* was slightly better with the Walk-in-Place than with the other two navigational interfaces, which could be an indicator that different navigational interfaces can impact the behavioral compliance with warnings differently in certain situations. Another possible explanation, especially for *Area 2 – Escape Routes* and regarding the Walk-in-Place could be the necessity to avoid wrong choices that would require more time/effort to recover from the error or, since the Walk-in-Place is closer to the walking movement, there is a higher cognitive availability which possibly allowed participants to pay more attention to the exit signs.

Several **performance variables** (i.e., *Duration*, *Distance*, *Pauses*, *Average speed*) were collected automatically by the VR system during the simulation. Since each area of the VE had a different type of task, it was expected to find statistically significant differences between the different navigational interfaces, in the performance variables between the two areas. Except for the *maximum duration of pauses*, in *Area 2 – Escape Routes*, statistical significant differences were found for all the other variables.

In terms of *Duration*, the Joystick presented the lower values in both areas, with a more pronounced difference in *Area 2 – Escape Routes*. This could be an indication that for emergency egress situations, the Joystick is easier to control than the other two navigational interfaces. However, since participants might have a sensation of "flying" through the VE, since the point of view's height is constant, this could also mean a somewhat unrealistic behavior in the navigation.

Regarding *Distance*, results show that the Walk-in-Place interface presented the lowest distances, in both areas, which was expected. These results are aligned to what was observed by Riecke (2010) that interfaces that allow physical rotation present shorter navigation paths. However, the Balance Board had higher values than the Joystick for the *Duration* variable, which was not expected. This might be due to more difficulties in controlling the interface, therefore requiring participants to make more corrections.

Regarding *Pauses* (which was subdivided into *Number*, *Maximum duration* and *Median duration*), results show that the navigational interfaces controlled by the lower body, made more pauses and with higher maximum durations. The higher number of pauses is in accordance to the higher values of *Duration* for the Balance Board and the Walk-in-Place. However, regarding the median duration of those pauses, the Balance Board had the lowest values for *Area 1 – Rooms*. Perhaps the cause for the differences that were found for the Balance Board for the *Distance* variable, might be also at play in this case. If participants had more difficulties controlling the interface, and required them to make more corrections, affecting in this way the duration of each pause. Regarding *Area 2 – Escape Routes*, the Walk-in-Place and the Balance Board had lower values than the Joystick. This was not expected and it might be due to the low number of pauses that participants that used the Joystick did in *Area 2 – Escape Routes*. Even though there were less pauses, they might have been longer than with the other interfaces, increasing therefore the median duration value.

In terms of *Average Speed*, it was expected to have higher values for the interface with which it is easier to start the movement and reach higher speeds faster (i.e., Joystick). That was confirmed by the obtained results. The Walk-in-Place was the interface that had the lowest values for *Average Speed*. Nonetheless, a lower value of average speed is not necessarily something negative as it can be seen by the slight higher values of compliance (especially for the compliance with uncued and exit signs), which might be an indication that these lower average speeds allowed participants to pay more attention in the VE.

Regarding the **sense of presence** variables which were measured by grouping certain items from the questionnaire (based on the Witmer and Singer Presence Questionnaire (1998)) and working with the mean values resulting from that grouping. The sense of presence variables are *Quality of Sensorial Experience* (QSE), *Quality of Interaction* (QI), *Quality of Interaction for the Navigational Interface* (QINI), *Distraction Factors* (DF), *Realism Level* (RL), *Notion of time* (NT) and *Enjoyment* (ENJ).

Results do not confirm the expectation that the Walk-in-Place would have higher levels of sense of presence reported by participants. Except for the *Realism Level* variable (which took into consideration the complete simulation), no statistical significant differences were found for the sense of presence variables. This might be an indication that, for the type of task involved in the simulation, the navigational interface is not the most important element to improve the sense of presence. Additionally, a Gender effect was found for the *Quality of Interaction* variable, with males selecting higher values than females. One possible reason for this can be that usually, more males are players of first-person games and as such could respond with higher values in similar situations.

In conclusion, and based on the results, whenever the focus of a study is solely the cognitive type of task that is involved (in this case, behavioral compliance with warnings), the Joystick appears to be the most appropriate navigational interface since it is easy to control, with not much training necessary. However, for tasks where navigation takes a more central role, where it must concern itself with the energy consumption, the Walk-in-Place navigational interfaces is more appropriate, since it resembles more the natural movement and allows physical rotations. The possibility for doing physical rotations gives more proprioceptive information to the participant and a more natural way of changing directions. Results also give an indication that participants that used the Walk-in-Place suffered less from simulator sickness than with the other navigational interfaces.

Chapter IV - Final Conclusions

Due to ethical constraints, there are certain situations where it is not possible to study the participants' behavior. These situations are usually emergency-based situations where the participants' life could be at stake (e.g., fire in a building, explosion). Other situations are impractical to be studied in the real world with a good variable control due to other reasons, such as a study in an airport, where ideally it would be required to close, or limit the amount of passenger's movement in a specific terminal. These and others limitations can be overcome by the use of Virtual Reality (VR). This technology is a tool that could benefit research studies since it allows for a high diversity of contexts, with full control of variables and replicability of the scenarios, participants are safe in the interaction, data can be collected automatically with accuracy and effectiveness that might not be possible in a real contexts. Nonetheless this technology in not flawless (e.g., possibility of simulator sickness, limited types of interaction, realism level of environments).

However, in emergency situations and in situations where it is not practical to close the space for more controlled testing, VR presents itself as the ideal tool. Taking that into account, in the Ergonomics Laboratory of the Faculty of Human Kinetics, University of Lisbon, it was considered the use of VR for behavioral compliance with warnings and wayfinding studies. In the initial research for VR software, it was not possible to find any VR software that could fulfill the research needs for behavioral compliance with warnings and wayfinding studies. The solution found was the development of a VR model (based on a software called ErgoVR) that could specifically fulfill those needs, especially since it would be developed involving closely the potential users, according to a User-Centered Design (UCD) approach.

Besides that, and after several research studies with the ErgoVR system, the effects on results of navigation and the navigational interface used in Virtual Reality-based studies started to be a research concern on how different navigational interfaces could affect the obtained results. As such, this document is divided in two main blocks: Chapter II - Model Development (ErgoVR) and Chapter III - Navigational Interfaces.

On Chapter II - Model Development (ErgoVR) it is presented the ErgoVR system and the UCD approach that was used in its development. The ErgoVR system is a VR system composed by hardware and software. The focus given on this document was on the development of the software.

Despite several iterative software development methodologies exist (e.g., scrum, crystal clear, extreme programming), they focus mostly on the programming stages of the process and also are more adequate for teams of programmers (this project only had one person responsible for the programming of the system). For these reasons, the UCD approach was more appropriate because it allows that the potential users are more involved in the development process since the earliest stages, instead of only in the testing stages. Since the ErgoVR system is a tool for research and the potential users of it are researchers, their involvement since the beginning was fundamental in guiding and prioritizing the type of functionality that the system needed to have. The testing phases benefitted as well since the researchers were able to verify early that the features that they required were being fulfilled by the system. The constant and swift feedback from the researchers allowed that each iterative cycle was short for each set of features (ranging from a 1 day to at most 2 weeks on longer cycles, where more complex functionality had to be implemented). This short iterative cycle provided new versions of the ErgoVR system that would allow for more frequent testing. The UCD approach was beneficial for this kind of system and it is visible by the work that was carried out where the ErgoVR system was used as a tool (especially on the two case studies presented in topic 2.4 Evaluation of ErgoVR). From that, it was possible to observe that the ErgoVR system was:

- Able to present quasi-realistic VEs in real time (graphically and environmentally), where it is possible to create complex interactive scenarios. These VEs can be visually rich with animations, sounds, particle systems (to represent fire, smoke and other elements), among others;
- Able to provide data outputs that could be personalized according to the study at hand as well as relevant extrapolated data;
- Able to automatically collect data regarding human behavior variables. This is complemented by the amount of data that can be extrapolated from the recorded information (e.g., participant's path and directional decisions, distance travelled, time spent in the simulation, detection of pauses (number, duration and location), areas that were most visited, among others);
- Able to use an event-based interactive system which allow to activate several different types of actions (e.g., animations, sounds, objects) depending on what the participant does inside the VE;
- Able to have virtual characters present in the VEs, with controlled speech;
- A system based on well-defined conventions which facilitates the automation of key elements in the use of the system and, at the same time, with the purpose of being easier to be used by anyone;
- Flexible VE creation which allows that the modelling and definition of the events of the scenario to happen completely in the 3D modelling software of the choice of the researcher (e.g., 3ds Max, Maya);
- Flexible for the inclusion of new functionality programmatically;
- A system that supports different types of VR equipment (e.g., different types of motion sensors, Head-Mounted Displays as well as other visualization devices, sound devices, navigational interfaces);

- A system that although was developed mostly for behavioral compliance with warnings and wayfinding studies, can be used in other types of studies, as presented in 2.4.3 - Other studies.

Since the use of the ErgoVR system is not simply regarding its direct features, it should be of note that regarding the creation of the VEs (although the topic itself was not the focus of this work it was mentioned thoroughly in this document) from the experience gathered from the different research studies where the ErgoVR system was an integral part, it is clear that the creation of the VEs is a discipline that should not be neglected or taken lightly in the development process of a research project. It is a complex topic that encompasses detailed knowledge of several different fields to create the scenario, tasks and the VE itself. These tasks require a strong multidisciplinary team with at least one member with a deep, technical understanding of VR and VEs and their limitations since these limitations will play a decisive role in how and if certain elements can be a part of the VE.

Two case studies were presented, one regarding a study on the topic of behavioral compliance with warnings and two other studies on the topic of wayfinding. The studies used the ErgoVR system, albeit different states (the Normal Simulation state for the first case and Decision Taking and Decision Taking Simulation states for the second case).

For either case, the flexibility in configuration of the ErgoVR system, as well as the type of information that was produced from the simulations, were fundamental for the researchers of those studies to focus on their research and using the ErgoVR system as a tool, instead of having to learn the intrinsic details of the system (by having to program it) to suit their research needs.

For both cases, the ErgoVR system provided the possibility of a centralized location for modelling and defining the actions of the VE through the creation of the models in a single 3D modelling application, 3ds Max. Nonetheless, as long as the 3D modelling software is able to export to the OGRE mesh format and also allows to have extra textual information associated with objects, the ErgoVR system can interpret and present that VE.

For the behavioral compliance with warnings study it was advantageous to have the possibility to define points in the VE where particle systems could be placed. These particle systems were the points of fire and smoke in the VE. Also, defining locations for the different sounds was important to allow to define an origin location of the alarm and multimodal warnings sounds. The definition of triggers in the VE was important to define actions due to the participant's behaviors as well as having key locations to analyze the data in different sections. Regarding the LogViewer, for this particular study it was also important to have the possibility to create manual triggers. This feature allowed a flexibility in the data analysis after the data was collected, allowing in this case to divide the VE in different analysis areas. The space exploration matrices, when applied in groups of the different experimental conditions, allowed for a different view of the data, allowing to determine the most common walked locations in the VE.

Regarding the wayfinding studies presented, the ErgoVR system also allowed for a fine control in terms of the repetitions of presentation of the different corridors, as well as the duration of presentation of each stimulus and a variable inter-stimulus duration. Each study had different types of possible interaction (one only allowed making the choice by pressing a button on a gamepad and the other one allowed the participant to move in the corridor to make the decision by walking towards the desired choice). The ErgoVR system was flexible enough to allow to join some of the characteristics of the Decision Taking state (with more limited interactivity and presenting the VE as a sequence of corridors) with the Normal Simulation state (with more interactivity).

The data was recorded similarly to the other case, since it was based on the same principles (i.e., location of the participant in the VE, instant of time and triggers pressed). However, when processing the data through the LogViewer, the exported data was more specific for the needs of a Decision Taking type of study. For these studies that included the data sorted by the choices taken, per corridor.

Another study was made (Elisângela Vilar, Rebelo, Noriega, Teles, & Mayhorn, 2015) that used the ErgoVR system. In terms of new functionalities of the system used in this study, there was one that was not used in the studies already mentioned in the document. This study introduced the need to add virtual humans to the environment with different clothing and animations (body and facial). The virtual humans were used to interact verbally with the participant when they arrived at key points in the VE. Participants were told that they were entering the hotel for a conference and they were late for their presentation. Three virtual humans provided instructions to the participants with directions to the next point. The virtual humans had different facial animations, each for pre-determined and pre-recorded sentences and questions. The activation of these animations, and in the order to which they were presented to the participant were the responsibility of the researcher. The system allowed the easy association of each sentence and animation pair, with a keyboard shortcut. Each pair could only be played if there was not any other playing at the moment to prevent incoherent auditory or visual feedback to the participant. The study used the Decision Taking Simulation state with a 3D projection and a joystick to navigate through the hotel.

Despite the results gathered from the use of the ErgoVR system in different types and number of studies, the effects on results of navigation and the navigational interface used started to be a research concern.

As such, with a focus on behavioral compliance with warnings, the second part of this work was the use of different navigational interfaces (i.e., Nintendo® Balance Board and a Walk-in-Place interface that was developed for this study) and comparing them with the results of a more traditional navigational interface for VR (a joystick) used by Duarte (Duarte et al., 2013). This study was made to verify if the observed behavior of participants would change depending on the navigational interface used. An end-of-day routine security check was the scenario used for this study, where participants were told that they would be replacing a coworker that got sick and as such they would have to follow written instructions left by that coworker throughout the environment. The VE had two distinctive areas: *Area 1 – Rooms* and *Area 2 – Escape Routes*. *Area 1 – Rooms* is the area where the written instructions as well as the *cued* (mentioned in the instructions) and *uncued* (not mentioned in the instructions) signs are present. It is composed of four rooms, each with an instruction and an action that the participant had to interpreted and perform. The instructions were presented in a sequence of rooms that needed to be visited. In the last room, a fire would start and participants needed to leave the building through *Area 2 – Escape Routes*. This area is composed by 6 t-shaped corridors which only one possible path to the exit. An *exit sign* was present in each intersection directing participants to the correct path. A total of 123 people participated in this study, where only 90 participants were part of the final sample (due to simulator sickness, equipment malfunctions, participants wanted to stop), separated equally by number and gender through the 3 experimental conditions (Joystick, Balance Board, Walk-in-Place).

Behavioral compliance with warnings was measured for *Area 1 – Rooms* by the number of buttons that participants pressed for either type of sign. For *Area 2 – Escape Routes*, behavioral compliance was measured by the number of correct (same choice as indicated by the *exit sign*) decisions made at the first try in each intersection.

The results gathered for Behavioral compliance, are in accordance with Duarte's (2013) results, with no statistical significant differences found between the three navigational interfaces. This might mean that the navigational interface does not affect the completion of the task. Consequently, neither one of the three navigational interfaces used in this study, affected the behavioral compliance of participants, as it was expected. However, and although no statistical significant differences were found, for the *compliance with uncued signs* and the *compliance with exits signs*, the results obtained with the Walk-in-Place were better than with the other two navigational interfaces, which could be an indicator that different navigational interfaces can impact the behavioral compliance with warnings differently in certain situations. Another possible explanation could be that the Walk-in-Place interface, since it is closer to the walking movement, allows for a higher cognitive availability for other tasks, which allowed participants to pay more attention to the exit signs.

Several performance variables (i.e., *Duration*, *Distance*, *Pauses*, *Average speed*) were collected automatically by the ErgoVR system during the simulation. Since each area of the VE had a different type of task, it was expected to find statistically significant differences between the different navigational interfaces, in the performance variables between the two areas. Except for the *maximum duration of pauses*, in *Area 2 – Escape Routes*, statistical significant differences were found for all the other variables. For the *Duration*, the Joystick presented the lower values in both areas, which might be an indication that the Joystick is easier to control. However, regarding *Distance*, the Walk-in-Place presented the lowest values, in both areas, that would confirm what was observed by Riecke (2010) that interfaces that allow physical rotation present shorter navigation paths. Regarding *Pauses* (which was subdivided into *Number*, *Maximum duration* and *Median duration*), results show that the navigational interfaces controlled by the lower body, made more pauses and with higher maximum durations. The higher number of pauses is in accordance to the higher values of *Duration* for the Balance Board and the Walk-in-Place. However, regarding the median duration of those pauses, the Balance Board had the lowest values for *Area 1 – Rooms*. Regarding *Area 2 – Escape Routes*, the Walk-in-Place and the Balance Board had lower values than the Joystick. This was not expected and it might be due to the low number of pauses that participants that used the Joystick did in *Area 2 – Escape Routes*. Even though there were less pauses, they might have been longer than with the other interfaces, increasing therefore the median duration value. Regarding *Average Speed*, the Joystick presented the higher values since it is the navigational interface that is easier to start the movement and reach higher speeds faster, and the Walk-in-Place was the interface that presented the lower values. The following sense of presence variables were measured: *Quality of Sensorial Experience*, *Quality of Interaction*, *Quality of Interaction for the Navigational Interface*, *Distraction Factors*, *Realism Level*, *Notion of time* and *Enjoyment*. Results do not confirm the expectation that the Walk-in-Place would have higher levels of sense of presence reported by participants. Except for the *Realism Level* variable (which took into consideration the complete simulation), no statistical significant differences were found for the sense of presence variables. This might be an indication that, for the type of task involved in the simulation, the navigational interface is not the most important element to improve the sense of presence. Additionally, a Gender effect was found for the *Quality of Interaction* variable, with males selecting higher values than females. One possible reason for this can be that usually, more males are players of first-person games and as such could respond with higher values in similar situations.

In conclusion, and based on the results, whenever the focus of a study is solely the cognitive type of task that is involved (in this case, behavioral compliance with warnings), the Joystick appears to be the most appropriate navigational interface since it is easy to control, with not much training necessary. However, for tasks where navigation takes a more central role, where it must concern itself with the energy consumption, the Walk-in-Place navigational interface is more appropriate, since it resembles more the natural movement and allows real physical rotations. The possibility for doing physical rotations gives more proprioceptive information to the participant and a more natural way of changing directions. Results also give an indication that participants that used the Walk-in-Place suffered less from simulator sickness than with the other navigational interfaces.

4.1 Future work

Eye-tracking technology is being used actively in research for different goals. When allied to VR, the information that can be gathered by an eye-tracker system can be used to detect exactly the objects that a person looked at and even if a certain even captured the attention of the user. The latter situation is interesting for example, in studying warnings to better understand the earlier stages of the C-HIP model (Conzola & Wogalter, 2001) in VR. Also, an eye-tracker system can be used as a form of interaction device for VR (e.g., Tanriverdi & Jacob, 2000).

As such, the integration of an eye-tracker system with the ErgoVR system is a future goal since that with real time detection and data recording, it would be possible to know exactly which objects the participant looked at and depending on the eye-tracker system used, which specific features of the object. This depends on the angular resolution of the output device and also at the minimum angular detection of the eye-tracker system used.

Regarding pauses, a more robust data analysis would need to be done, when regarding the possibility of “false” positives in the detection of a pause. As mentioned earlier, a pause is considered when the participant is stationary in the VE for 2000ms. A “false” positive could happen on situations where the person stopped and it is close to that 2000ms mark and decides to start moving. The latency between wanting to start moving and the actual movement happening can be large enough that it would be considered a pause whereas it might not be. Different interfaces have a different latency associated with it to initiate the movement. With the Joystick a small movement with the wrist/hand is enough to initiate the movement. With the Balance Board, it is necessary to shift the body’s weight to a new position which naturally takes more time than the Joystick. And finally, with the Walk-in-Place, it is required for the participants to start lifting their leg to start moving, which takes considerably longer. In the definition of the protocol for this study, the start of movement latency for each interface was not taken into account while calculating the pauses duration and as such, no measures were made accordingly at the time. For a future study, the latency for each navigational interface should be taken into account.

Regarding the sense of presence analysis, there are studies which make use of physiological reactions, such as heart rate, skin conductance, skin temperature, EEG (e.g., Clemente, Rodríguez, Rey, & Alcañiz, 2014; Meehan, Insko, Whitton, & Brooks, 2002; Meehan, 2001), in order to have access to more objective data relative to the sense of presence. In (Meehan, Razzaque, Insko, Whitton, & Brooks, 2005) it was hypothesized that, as in real environments, VEs would evoke certain physiological responses and as such, a greater presence would evoke a greater response. They found that change in heart rate satisfied their requirements for a measure of presence whereas skin conductance and temperature did not. Regarding EEG, Clemente and colleagues (2014) obtained significant differences when comparing a navigation and a video condition (active versus active navigation) and also between different screen types (desktop screen and projection screen), while navigating. Although the presence questionnaire used gives interesting results, it is still based on subjective factors. As such, in future studies, analyzing elements such as heart rate and/or EEG could add a surplus value to the studies in Virtual Reality.

The navigational interfaces comparative study was made using a behavioral compliance with warnings perspective. A similar comparative study using a wayfinding perspective would be interesting to do, especially to understand the effects of the energy consumption of participants when using the Walk-in-Place interface on the decisions that people make while navigating in a building. Also, to robustly ascertain the influence of the performance variables studied, a more specific protocol focused on this type of variables should be developed.

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Annexes

Annex A – Consent Form

Participante __________

FACULDADE DE MOTRICIDADE HUMANA

Termo de consentimento livre e informado

Título da pesquisa: Experimentação de um sistema de Realidade Virtual para recolha de dados relativos ao comportamento humano.

Investigadores: Luís Teixeira e Francisco Rebelo

Foi convidado(a) a participar, como voluntário(a), numa pesquisa, no âmbito de um trabalho de doutoramento, a decorrer na Faculdade de Motricidade Humana, da Universidade de Lisboa (FMH/UL), na especialidade de Ergonomia. A sua participação representa um importante contributo, não só para o estudo em curso, mas também para o desenvolvimento do conhecimento na área da Ergonomia. Ao participar, terá a oportunidade de experimentar equipamentos e tecnologias associadas à Realidade Virtual (RV), que não são de uso comum.

É importante que leia a informação seguinte, antes de concordar em participar nesta pesquisa. Este texto descreve, de forma sucinta, a pesquisa, seus objectivos gerais e o que se espera da sua participação, incluindo a identificação dos procedimentos experimentais, riscos previstos, seus direitos e confidencialidade dos dados. Caso aceite fazer parte deste estudo, deverá assinar as duas vias deste documento, sendo que, uma delas ficará na sua posse e a outra com o pesquisador responsável.

Explicação do procedimento

Este estudo tem por objectivo avaliar um sistema de Realidade Virtual, para registo de dados relativos ao comportamento humano em ambiente virtuais.

A sessão experimental está dividida em 3 partes: (1) sessão de treino e calibragem dos equipamentos; (2) sessão de simulação em RV e (3) resposta a um questionário que contêm 44 questões. O tempo total estimado para a sua participação é de, aproximadamente, 30 minutos.

A simulação em RV implica o uso de óculos/capacete de RV, sensores de movimento, auscultadores. Terá a possibilidade de experimentar estes equipamentos, numa sessão de treino, até sentir que está apto(a) a participar.

Riscos e desconforto

Como é normal em qualquer jogo de computador, nesta simulação terá que realizar algumas tarefas, dentro do mundo virtual, para as quais receberá informação detalhada no início da simulação. Poderá ser confrontado com situações simuladas que representam perigo para a sua personagem virtual. Naturalmente, pode acontecer que algumas pessoas mais sensíveis possam sentir algum tipo de ansiedade ou, em função de características individuais, sentir enjoo do simulador.

Abandono da experiência sem qualquer penalização

A participação nesta pesquisa é voluntária, pelo que, pode decidir interromper a sessão e abandonar o estudo a qualquer momento, sem qualquer penalização. Também pode optar por não responder a qualquer questão do questionário.

Confidencialidade dos dados

Todos os dados recolhidos serão confidenciais, incluindo as suas respostas ao questionário que serão anónimas. Para isso, os participantes serão identificados apenas com um número, que serve para o investigador ter registo da sequência pela qual a experiência decorreu. A sessão de simulação em RV será filmada, para análise posterior.

Contactos

Para esclarecimentos adicionais ou questões relacionadas com esta pesquisa poderão contactar os investigadores para o telefone - 214149160 ou por e-mail – lmteixeira@fmh.utl.pt

Consentimento

Ao assinar este documento está a declarar a sua vontade em participar neste estudo e a confirmar que recebeu uma cópia deste consentimento livre e informado. Declara, também, que cede os direitos do uso das imagens gravadas durante a sessão, para publicação em revistas científicas, apresentação em encontros científicos e actividades de leccionação.

Questões de ética e segurança dos participantes	Sim	Não
Sofre de doenças cardíacas (ex. arritmia)?	☐	☐
Sofre de vertigens?	☐	☐
Sofre, ou sofreu recentemente, de depressão?	☐	☐
No caso de ser mulher, está grávida?	☐	☐

______________________________________ ________________
Assinatura do participante Data

____
Nome do participante

______________________________________ ________________
Assinatura do pesquisador Data

Annex B – Questionnaire

Dados demográficos

1. Quantos **anos** tem? _____________ anos

2. O seu **género** é? ☐ Masculino ☐ Feminino

3. Qual a sua **escolaridade**?

- ☐ Estudante de Licenciatura
- ☐ Estudante de Mestrado
- ☐ Estudante de Doutoramento
- ☐ Licenciado
- ☐ Mestre
- ☐ Doutor

4. A sua **profissão/ocupação** é? ____

5. Qual a sua experiência actual com jogos vídeo (ex: jogos de computador, X-Box, Playstation, Wii)?

- ☐ Nunca joguei
- ☐ Jogo esporadicamente
- ☐ Jogo entre 1 e 10 horas por semana
- ☐ Jogo entre 10 e 20 horas por semana
- ☐ Jogo entre 20 e 30 horas por semana
- ☐ Jogo mais de 30 horas por semana

6. É jogador frequente de **jogos vídeo acção/aventura** (mais de 7 horas semana, nos últimos 2 meses)?

☐ Sim ☐ Não

6.1. Se respondeu sim, à questão anterior, indique qual o seu perfil de jogador:

- ☐ Prefere jogos de primeira pessoa (ex: Doom; Quake)
- ☐ Prefere jogos de terceira pessoa (ex: Tomb Raider)
- ☐ Ambos

7. Classifique a sua experiência com simuladores de Realidade Virtual (RV), nos últimos 2 anos:

7.1. Experimentou simuladores que recorrem ao uso de óculos para realidade virtual;

☐ Nunca ☐ Pelo menos 1 vez ☐ Mais de 2 vezes

7.2. Experimentou simuladores que recorrem ao movimento da plataforma/assento sincronizado com imagens projectadas;

☐ Nunca ☐ Pelo menos 1 vez ☐ Mais de 2 vezes

7.3. Experimentou simuladores que recorrem a ambos os processos em simultâneo (óculos + movimento);

☐ Nunca ☐ Pelo menos 1 vez ☐ Mais de 2 vezes

Qualidade da experiência sensorial da simulação que acabou de realizar

Instruções de preenchimento: marque um "x" sobre o número, inscrito na quadrícula da escala, correspondente à sua avaliação.

8. Como classifica o **nível de estimulação sensorial global** experimentado durante a simulação (ex. envolvimento dos seus sentidos na experiência virtual)?

Muito baixo			Médio			Muito alto
1	2	3	4	5	6	7

9. Até que ponto os estímulos **visuais** o fizeram sentir-se "dentro" do envolvimento virtual?

Muito pouco			Médio			Bastante
1	2	3	4	5	6	7

10. Até que ponto os estímulos **auditivos** o fizeram sentir-se "dentro" do envolvimento virtual?

Muito pouco			Médio			Bastante
1	2	3	4	5	6	7

11. Até que ponto conseguiu **identificar/reconhecer os sons** presentes no mundo virtual?

Nunca			Às vezes			Sempre
1	2	3	4	5	6	7

12. Até que ponto conseguiu **localizar os sons no espaço**?

Nunca			Às vezes			Sempre
1	2	3	4	5	6	7

13. Até que ponto conseguiu **explorar/pesquisar visualmente** o mundo virtual?

Muito pouco			Médio			Bastante
1	2	3	4	5	6	7

14. Até que ponto conseguiu **visionar avisos de segurança/sinais de emergência** (ler os seus detalhes) existentes no mundo virtual?

Nunca			Às vezes			Sempre
1	2	3	4	5	6	7

Qualidade da interacção no mundo virtual

15. **Qualidade da deslocação o mundo virtual**

15.1. Qual o grau de **facilidade na sua deslocação** no mundo virtual, usando o dispositivo de navegação (ex: com que facilidade conseguia ir para um determinado ponto do espaço)?

Muito baixo			Razoável			Muito alto
1	2	3	4	5	6	7

15.2. Qual o grau de **controlo que teve sobre sua deslocação,** usando o dispositivo de navegação (ex: com que precisão se posicionava/parava no sítio desejado)?

Muito baixo			Razoável			Muito alto
1	2	3	4	5	6	7

15.3. Com que **rapidez se conseguiu adaptar** à **deslocação**, usando o dispositivo de navegação?

Muito lento			Médio			Muito rápido
1	2	3	4	5	6	7

15.4. No final da simulação como classifica o seu desempenho de **deslocação** no mundo virtual, usando o dispositivo de navegação?

Muito má			Razoável			Muito boa
1	2	3	4	5	6	7

16. **Qualidade da interacção oferecida pelos sensores de movimento**

16.1 Qual o grau de **naturalidade do comportamento do olhar** oferecido pelo sistema (ex: quando queria ver alguma coisa, no mundo virtual, movia a sua cabeça nessa direcção)?

Muito baixo			Razoável			Muito alto
1	2	3	4	5	6	7

16.2. Qual o grau de **controlo sobre o comportamento do olhar** (ex: qual a capacidade de direccionar a sua cabeça, com precisão, para uma determinada direcção)?

Muito baixo			Razoável			Muito alto
1	2	3	4	5	6	7

16.3. Qual o grau de **naturalidade na execução dos movimentos da mão virtual** (ex: quando queria tocar nos botões, no mundo virtual, movia a sua mão nessa direcção)?

Muito baixo			Razoável			Muito alto
1	2	3	4	5	6	7

16.4. Qual o grau de **controlo sobre os movimentos da mão virtual** (ex: qual a capacidade de tocar/accionar, com precisão, os botões existentes no mundo virtual)?

Muito baixo			Razoável			Muito alto
1	2	3	4	5	6	7

Factores de distracção

17. Até que ponto teve consciência da presença dos **óculos** durante a simulação?

Muito pouco			Médio			Bastante
1	2	3	4	5	6	7

18. Até que ponto a forma de navegação causou **distracção** no desempenho das tarefas pedidas?

Muito pouco			Médio			Bastante
1	2	3	4	5	6	7

19. Até que ponto a **qualidade da imagem**, exibida do mundo virtual, interferiu no desempenho das tarefas pedidas?

Muito pouco			Médio			Bastante
1	2	3	4	5	6	7

20. Até que ponto, durante a simulação, teve **consciência do que se estava a passar em seu redo**r, no mundo real (ex. ter consciência de sons provenientes do mundo real)?

Muito pouco			Médio			Bastante
1	2	3	4	5	6	7

Grau de realismo

21. Qual o **grau de realismo** que atribui à simulação que acabou de experienciar?

Muito baixo			Razoável			Muito alto
1	2	3	4	5	6	7

22. Até que ponto considera a sua experiência no mundo virtual **diferente** da sua experiência no mundo real?

Muito pouco			Razoável			Bastante
1	2	3	4	5	6	7

Noção do tempo

23. Esteve envolvido(a) na simulação ao ponto de perder a **noção do tempo**?

Nunca			Às vezes			Sempre
1	2	3	4	5	6	7

"Poluição" do envolvimento

24. Como classifica o grau de **"poluição visual"** (excesso de estímulos visuais, caos visual) do ambiente virtual?

Muito baixo			Razoável			Muito alto
1	2	3	4	5	6	7

25. Até que ponto o grau **"poluição visual"** interferiu no desempenho das tarefas pedidas?

Muito pouco			Médio			Bastante
1	2	3	4	5	6	7

26. Como classifica o grau de **"poluição auditiva"** (excesso de estímulos auditivos, caos sonoro) do ambiente virtual?

Muito baixo			Razoável			Muito alto
1	2	3	4	5	6	7

27. O grau **"poluição auditiva"** interferiu no desempenho das tarefas pedidas?

Muito pouco			Médio			Bastante
1	2	3	4	5	6	7

Avaliação global da simulação

28. Como classifica o seu grau de **envolvimento na simulação**?

Muito baixo			Razoável			Muito alto
1	2	3	4	5	6	7

29. Como classifica a **duração** da sua experiência na simulação de RV?

Muito curta			Médio			Muito longa
1	2	3	4	5	6	7

30. Como classifica a **coerência do contexto** (pequena história) introdutório face à simulação?

Muito pouco			Médio			Bastante
1	2	3	4	5	6	7

31. Como classifica o seu grau de **divertimento na simulação**?

Muito baixo			Razoável			Muito alto
1	2	3	4	5	6	7

Perigo percepcionado e probabilidade de lesão

32. Qual o grau de **perigo,** que esteve exposto o seu "corpo virtual", na simulação?

Muito baixo			Razoável			Muito alto
1	2	3	4	5	6	7

33. Qual a probabilidade do seu "corpo virtual" sofrer **ferimentos/lesões,** dentro da simulação?

Muito pouco			Médio			Bastante
1	2	3	4	5	6	7

34. Que gravidade atribuiria a esses **ferimentos**?

Muito pouco			Médio			Bastante
1	2	3	4	5	6	7

35. Que influência tiveram os **avisos de segurança** (ex. avisos posicionados junto dos botões), presentes no mundo virtual, no seu comportamento?

Nenhuma			Alguma			Total
1	2	3	4	5	6	7

36. Que influência tiveram os **sinais de saída de emergência,** presentes no mundo virtual, no seu comportamento?

Nenhuma			Alguma			Total
1	2	3	4	5	6	7