Flashing lights at road tunnel emergency exit portals: A Virtual Reality study with low-cost Head Mounted Displays

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Abstract

Previous studies have provided detailed recommendations regarding the design of flashing lights at emergency exit portals in road tunnels. Theory of Affordances have assisted safety designers fixing characteristics such as color, flashing rate, type and number of lights in emergency systems. A systematic evaluation through experiments has, additionally, provide stronger support to define these characteristics.

The present project replicates the Virtual Reality (VR) experiment on the design of flashing lights from Ronchi and Nilsson (2015) conducted in a Cave Automatic Virtual Environment (CAVE) with the usage of low-cost VR equipment in order to create a cross comparison between VR technologies and provide stronger support to VR as a research method in several fields of application. The main motivation to perform this comparison arises from premises such as technological advances and accessibility that Head Mounted Displays (HMD) offer nowadays. A HMD powered by a mobile device was, therefore, tested with the purpose of defining if it is a system immerse enough to provide the results offered by more robust technologies.

After facing changes and limitations regarding image performance, the results obtained in the cross comparison, which show a high level of similarity (93.33%), justify the usage of low-cost HMD as a research tool in Human Behavior in Fire. Additional justification is reached since the results were also found to be cost-effective and easily obtained.

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Disclaimer

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Read and Approved,

David Andres Mayorga Puente

April 30th, 2017

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Abstract (Español)

Estudios anteriores han proporcionado recomendaciones detalladas sobre el diseño de luces intermitentes en portales de salida de emergencia en túneles de carretera. La Teoría de *Affordances* ha ayudado a los diseñadores de seguridad a establecer características tales como color, frecuencia, tipo y número de luces en sistemas de emergencia. Una evaluación sistemática a través de experimentos ha proporcionado, además, un apoyo más fuerte para definir estas características.

El presente proyecto reproduce el experimento de Realidad Virtual (RV) sobre el diseño de luces intermitentes de Ronchi y Nilsson (2015) realizado en el Ambiente Virtual Automático tipo Cueva (CAVE por sus siglas en inglés) con el uso de equipos de RV de bajo costo para crear una comparación cruzada entre las tecnologías de RV y brindar un mayor apoyo a la RV como método de investigación en varios campos de aplicación. La principal motivación para realizar esta comparación se deriva de premisas tales como los avances tecnológicos y la accesibilidad que las Gafas de Realidad Virtual (GRV) ofrecen hoy en día. Una GRV que trabaja con un dispositivo móvil fue, por lo tanto, probada con el propósito de definir si es un sistema que permite al usuario un nivel de inmersión lo suficientemente alto como para proporcionar los resultados ofrecidos por tecnologías más robustas.

Después de afrontar cambios y limitaciones en cuanto al rendimiento de imágenes, los resultados obtenidos en la comparación cruzada, que muestran un alto nivel de similitud (93.33%), justifican el uso de HMD de bajo costo como una herramienta de investigación en Comportamiento Humano durante Incendios. Justificación adicional es alcanzada ya que se encontró que los resultados también fueron rentables y fáciles de obtener.

Acknowledgments

The present project represents not only the last step in my Master Program but also a big one in my life. I started this international adventure with the legend “Never stop learning because the moment you do, you will stop living” and, in this period of time, I have lived indeed. This section is dedicated to all who have helped me living these past two years.

To my daughter in the water Emiliana, for being the everyday motivation required to continue in the correct path. A cellphone screen will soon become flesh and bone forever.

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To my mother, father and sister, for being the ones that seeded my path, believed in me and supported me every moment. Count on me always.

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And last but not least, to all the friends I have met in here and there who have become like family to me. Cheers for the extraordinary living experiences we shared shoulder to shoulder.

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Nomenclature

CAVE	Cave Automatic Virtual Environment
FS	Fire Safety
HBiF	Human Behavior in Fire
HMD	Head Mounted Display
VE	Virtual Environment
VR	Virtual Reality

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1 Introduction

Fire Safety (FS) has been mainly ruled by a “Design by Disaster” slogan, e.g. the Great Fire of London in 1666 led the UK government to analyze the major fire safety failings (Fire Safety Services, 2016) and propose regulations to avoid in future with new Fire Protection measures. Many cases since then have guided researchers into using correlational and scientific research studies to investigate about the expected safety which is mainly aimed to the reduction of casualties. Nevertheless, current research development endeavors that this reduction of casualties in fire cannot only be achieved by fire science or by adding more prescriptive requirements regarding buildings but also by developing the knowledge of Human Behavior in Fire (HBiF) (Shields & Proulx, 2000).

In order to go deeper into the research challenges regarding Fire Safety, research efforts in the area of evacuation are required. Many issues must be overcome in this field and several constrains are faced. Most of these constrains arise from the research methodology and they have mainly to do with ethics, economic issues, familiarity with the environment, ecological validity and sources of bias. Changing the nature, the degree of control, the data collection technique and the research method itself (Nilsson, 2009) can help dealing with these constrains but not fully satisfy them.

If moving forward to evacuations in tunnels, it can be argued that the same previously mentioned constrains apply but a higher degree of attention is required for some of them. Road tunnels are indeed critical transportation infrastructures in terms of evacuation safety (Ronchi & Nilsson, 2015). Its risk can be considered greater despite the low probabilities of accident due to the fact that consequences can be significantly disastrous. Therefore, it can be said that special attention must be paid in the selected research method to be used. Several studies have been made regarding evacuation in tunnels, e.g. (Ronchi, 2013) and (Nilsson, Johansson, & Frantzich, 2009). Many of them have focused in HBiF aspects such as social influence, emergency exit designs and toxicity and independently on the topic of study, a trend towards applying new research methods has been set. The motivation to use these new research methods relies on the premise of reaching a balance between the issues that were previously investigated and new research tools, e.g., Virtual Reality (VR). Different fields of study are taken into account when conducting research about evacuation in tunnels with VR. These are presented in Figure 1.

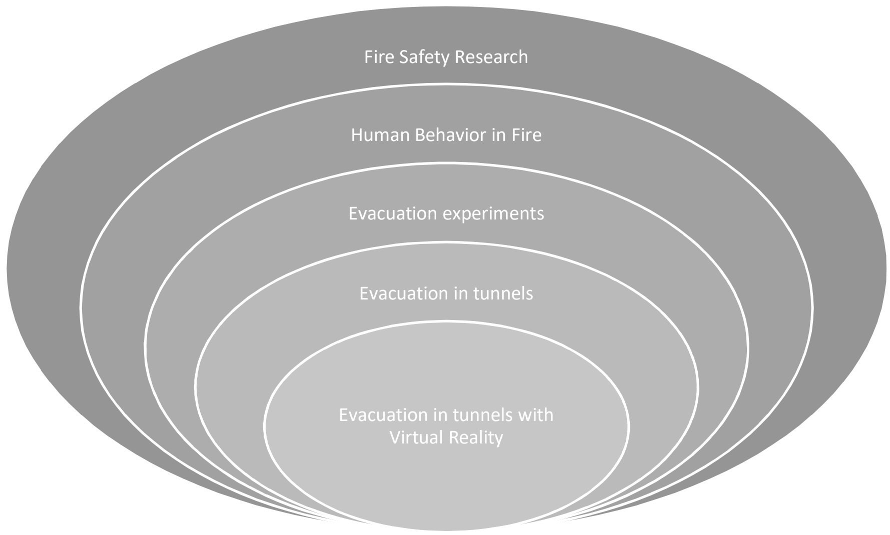

Figure 1. Aspects taken into account for studies regarding evacuation in tunnels with Virtual Reality.

Virtual Reality provides several benefits when used as a research method (Kinateder, Nilsson, Kobes, Pauli, & Mühlberger, 2014) and studies concerning evacuation in tunnels have been lately taking advantage of these benefits by using VR tools. The present work aims to use low-cost VR technology to reproduce results from a previous experiment (Ronchi & Nilsson, A Virtual Reality experiment on the design of flashing lights at emergency exit portals for road tunnel evacuations, 2015) and discuss the advantages and flaws found during the experimental process.

1.1 Background

As mentioned before, the level of safety required in tunnels is highly demanding and systems that could guide the evacuees towards safe places are able to decrease the total evacuation time and exposure to risk, hence increase the level of safety. The effectiveness of way-finding systems is reflected in the likelihood that the occupants have of using an emergency exit. (Ronchi & Nilsson, 2015)

Several sub-systems have been proposed and are used to increase the effectiveness of way-finding in tunnels. Among the most common ones for smoke-filled environments, the use of flashing lights stands out. Nilsson (2009) encourages the use of flashing lights in order to aid route choice. Cosma (2016) and Nilsson (2009) have investigated the features of flashing lights in emergency exits. Ronchi and Nilsson (2015) performed a systematic evaluation to experimentally investigate the main characteristics concerning the design of flashing lights at tunnel emergency exit portals. These characteristics or variables are listed below:

- The color of the light,
- The flashing rate,
- The type of light source,

- The number and layout of the lights and
- The use of either a window or a painted running man on the exit door.

The work performed by Ronchi and Nilsson (2015) adopted Virtual Reality for the systematic study of the previously exposed variables and made participants evaluate portal designs using a questionnaire based on the Theory of Affordances (Gibson, 1977), (1986). Their study had two main objectives. The first one was to present a method for the evaluation of tunnel safety installations. The second one was to assist road tunnel safety engineers and operators in the design of the characteristic of flashing lights for road tunnel emergency exit portals.

During the experiment, Virtual Reality was used to evaluate the effectiveness of different setups of exit portals designs by mainly changing characteristics in the flashing lights. At the time of the experiment (2015), a Cave Automatic Virtual Environment (CAVE) system at Lund University called the Black Box was used and considered the state of the art. This equipment consists of a back projection system with 4 screens that use stereoscopy technology with polarized lights. A portion of the tunnel was the base of the VR scenario and emergency exit portals installation set ups varied according to the information presented in Table 1.

Table 1. Installation setups used to study each variable in the design of emergency exit portals. Taken from (Ronchi & Nilsson, 2015).

Variable	Installation setups
Color	Green
	White
	Blue
Flashing Rate	0.25 Hz
	1 Hz
	4 Hz
Type of light source	Strobe
	Light-Emitting Diode (LED)
	Double strobe
Layout of the lights	2 Bars
	3 lights (2 on the sides and 1 on top)
	1 light
Door design	Painted running man
	Window

Previous research done by Ronchi and Nilsson (2015) determined that a base and reference emergency exit portal design in line with European standards, e.g. (AFS, 2008), contemplates green colored lights, a flashing rate equivalent to 1 Hz (Figure 2) which encourages emergency exit usage, Light-Emitting Diodes (Figure 2) as type of lights due to being electrical efficient and future technology in tunnels, 3 lights as common engineering practice (Figure 3) and a window in the center of the door (Figure 3) to provide confidence in the evacuees regarding reaching a safe place. This reference scenario (RS) was lately used in the analysis part to be compared with the alternative designs and statistically evaluate them using the premises of the Theory of Affordances. For further information regarding the installation setups and details regarding the exact features of the flashing lights refer to sections 3.1 and 3.2 of the base experiment (Ronchi & Nilsson, 2015). Section 3.2 in the present document details the experiment done for this project and additional information is given due to it is replicated.

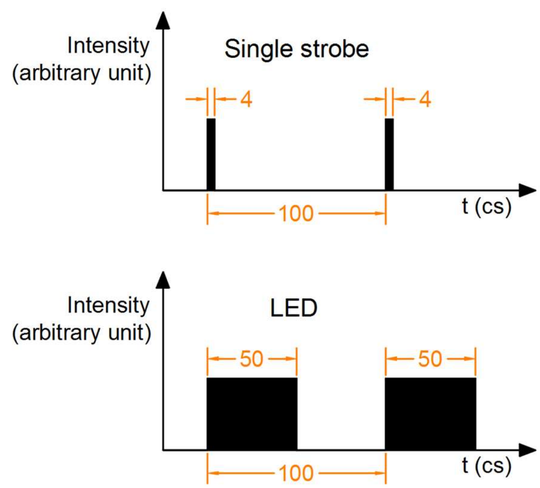

Figure 2. Schematic representation of the types (i.e., light pattern) of light sources used for this project. Edited from (Ronchi & Nilsson, 2015).

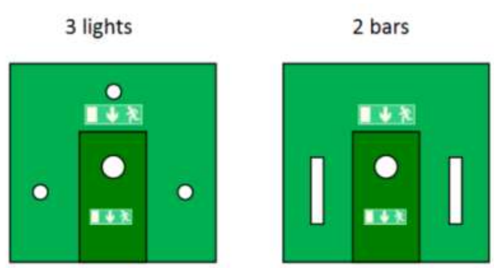

Figure 3. Schematic representation of the layouts of lights used. Edited from (Ronchi & Nilsson, 2015).

The base experiment took place in Lund in May and June 2014. It involved 96 participants and consisted of two parts. During the first part, participants navigated in a VR tunnel in the CAVE system (Black box + head tracking device + 3D glasses + gamepad) and were required to find their way out to safety, e.g. through an emergency exit. Behavior and path followed by the participants were observed by two researchers. Part 2 of the experiment involved alternative emergency exit designs which were presented to the participants in a varying order (seven in total to each participant) and ask them to provide a rank by means of a questionnaire whose responses used a Likert scale between -3 and +3. For further information regarding the experiment procedure refer to section 3.2.2 of the base experiment (Ronchi & Nilsson, 2015). Section 3.2.2.3 in the present document explains the corresponding information for the actual experiment.

The results of the study served as assistance in the design of the evacuation systems in the Stockholm bypass project (2015). The study demonstrated that flashing lights have a positive impact on emergency exit usage. The recommended colors resulted green or white. Flashing rates between 1 and 4 Hz performed better. LED lights performed significantly better. Position and number of lights presented no significant differences. A door design with a window on it provided better scores that one with a running man painted.

The previous findings contributed to the ecological validation of VR as a research method and validated the characteristics associated to the Theory of Affordances. Future studies were recommended in order to investigate and discuss the limitations and advantages of VR in relation to other fields of application.

The present work proposes the usage of low-cost VR equipment to replicate the previous experiment and compare the results to provide stronger support to the already obtained validation and increase the variety of technologies that could be used in other fields of application.

1.2 Purpose and Objectives

After going through the information provided in the introduction and background sections, a question emerges and sets the foundations of the present project.

> *To which extent Head Mounted Displays (HMDs) using mobile devices are immerse enough systems to provide the results offered by more robust technologies?*

Validity studies usually point towards ecological validation (Kinateder et al, 2014). In this instance a cross comparison between VR technologies is performed. This external validity should be also kept in mind as technology not only advances and changes at huge steps but it also becomes more accessible to people.

The purpose of this thesis is, as first introduced in the question at issue, to provide validity comparison between two different VR technologies using as method the replication of an experiment previously developed in an environment with flashing lights at emergency exit portals in road tunnels (Ronchi & Nilsson, A Virtual Reality experiment on the design of flashing lights at emergency exit portals for road tunnel evacuations, 2015). The technology used in this experiment was a CAVE system and the one proposed for this thesis project is a Head Mounted Display working with a mobile device.

When using different research tools it was also taken into consideration the premise to keep changes to the minimum in order to draw conclusions regarding whether or not the new equipment employed can provide comparable results and replace, not only the previously used technology but other traditional research methods.

In order to achieve the expected result, it is required that the findings obtained in this new experiment are to some degree similar to the ones obtained previously. Likewise, it is important to mention that modifications (specifically reductions) regarding number of participants and installation setups are also considered as long as these do not imply loss of information and they provide enough data to be compared with the base experiment.

Two concrete objectives are set in this project, they are listed below.

- To provide comparison between experiments done with a Cave Automatic Virtual Environment (CAVE) system and a Head Mounted Display (HMD) by investigating the level of resemblance in the results.
- To discuss the advantages and difficulties found when performing experiments in Human Behavior in Fire using Virtual Reality with Head Mounted Displays powered by mobile devices.

1.3 Methodology

In order to meet the previously proposed objectives and get an answer to the question at issue referred in the introductory part, the following methodology was employed:

a. Literature study

Expanding the main core of the introduction part of this document, theories and previously researched information are analyzed. This is done to provide support to the research and help the reader understand some basic knowledge behind the nature of this project. The research areas concerning the experiment are referenced and detailed.

b. Setup and Experiment

Considering that the Virtual Environment (VE) from the previous experiment was obtained, slight modifications regarding graphical improvement and scenarios removal took place during the setup phase of the experiment (VR environment build-up). The process of transferring the 3D environment to the mobile device also took place at this stage. Development of questionnaire-filling using online tools was also implemented prior the experiment in order to obtain direct digital data. Recruitment and contact with the participants was done parallel.

An estimate of 50 - 60 people were initially expected to join the experiment and 55 was the total number of participants reached. Each one of them had a very similar experience compared to the base experiment but with the main difference that only six installation setups were used (Reference scenario, blue lights, fast flashing, single strobe, 2 bars and no lights). It is also important to note that participants also tested the experiment for a different project subsequently.

c. **Data Analysis, discussion and conclusions.**

The obtained data is organized, presented, analyzed and compared with the one previously obtained in the base experiment (Ronchi & Nilsson, 2015). A direct evaluation between results is done by comparing descriptive and inferential statistics. Conclusions are drawn out of these previous steps and a discussion is provided in order to set information aligned to the purpose and aim of the project.

1.4 Limitations and Delimitations

Since the new experiment considered in this project is based on an earlier one, limitations and delimitations come mainly from the experimental plan previously developed. The fact that a different technology (HMD powered by a mobile device) is used also introduces limitations. For both aspects, a list is provided below.

- The previous experiment consisted of 96 participants. Due to time and resources restrains, this project only evaluated the results of 55 participants.
- Nationalities and main occupation of individuals varied significantly if compared to the ones previously tested. The present sample consisted mainly on International students in contrast with the previous experiment where participants where mainly Swedish and their occupation varied more.
- The previous experiment consisted on a training session and two different main parts. So did the present one but a considerable change was made in the second part where only six out of eleven available scenarios were analyzed.
- Performance, graphics and control limitations were initially expected due to relatively low-cost devices were used.
- Questionnaire fatigue control and tracking of participants view-points are not included in the present research.

2 Literature study

Several articles regarding Virtual Reality in Fire Evacuation Research will be used to establish the foundations of the thesis and to build arguments regarding its purpose and aim. However, it is important to denote that (Ronchi & Nilsson, 2015) is the main document to be used due to the present work corresponds to a comparison of the experiment performed in this reference.

2.1 Virtual Reality in Human Behavior in Fire

When referring to fire evacuation studies, the biggest challenge is accessing to ecologically valid and experimentally controlled empirical data (Kinateder et al, 2014). Several research methods have been employed over the past years providing information that somehow help understanding Human Behavior in Fire. Factors such as destination choice and evacuation time permit evaluating different design solutions, factors affecting HBiF itself or emergency management strategies (Nilsson, 2009). All these have been studied using traditional research methods that include, among the most used ones, Laboratory experiments, Field studies, Case studies and Drills.

Moving forward, Virtual Reality, which can be defined as a "real or simulated environment in which the perceiver experiences telepresence[1]" (Steuer, 1992) and VR experiments are becoming an increasingly popular research method in the area of HBiF (Nilsson & Kinateder, 2015). With a variation of components and technologies, VR has permitted to develop studies and trainings in Virtual Environments in which the participant gets immerse at different levels depending on the features of these components. For instance, low immersive VR systems such as computer simulators have been used for decades and lately, experiments developed in Cave Automatic Virtual Environments (CAVE) or using Head Mounted Displays (HMD) are new trends and have been used for experiments such as the ones developed by Ronchi and Nilsson (2015) or Kawai et al. (2016) respectively. Additionally, in the HBiF field, Kobes et al. (2010) have performed experiments regarding way finding in drills. Training in firefighting have also been benefited from VR technologies (Tate, Sibert, & King, 1977).

It is also important to make a distinction between HMD themselves since nowadays, the VR market offers a wide range of different technologies which not only vary by price but also from working principle and processing capabilities. As reference, (Oculus Rift., 2017) and (Samsung Gear VR, 2017) will be used in order to provide further comprehension of these mentioned differences in technologies.

Oculus Rift is a headset that possess the display already mounted in its body and video is transmitted, for instance, via HDMI (High-Definition Multimedia Interface). It additionally uses a gyroscope, accelerometer, and a compass to track the location of

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[1] The feeling of being present in a virtual environment.

user's head. One of its main distinctions is that the processing is done in a laptop or a personal computer (PC) which transfers the images, as mentioned before, through an HDMI cable. It is developed and manufactured by Oculus VR which is a division of Facebook Inc. and its current version was released on March 28th, 2016.

Figure 4. Oculus Rift. (Oculus Rift., 2017)

On the other hand, Head Mounted Displays such as the Samsung Gear VR[2] (Samsung Gear VR, 2017) or Google Cardboard (Google Cardboard, 2017) use the full capacity (display, sensors and processor) of a mobile device. It is developed and manufactured by Samsung Electronics in collaboration with Oculus VR. The version used for this project was released on October 11th, 2016.

Figure 5. Samsung Gear VR headset. (Samsung Gear VR, 2017)

Users might wonder why to choose a device that provides less technical capabilities? Amin et al. (2016) have shown that, despite its simplicity and small screen size, HMD

[2] Samsung's headset was used in this project.

using cellphones are still capable of providing an acceptable level of immersion compared to larger screen sized ones such as Oculus Rift.

Having established the appropriate technology, the statement that experiments in Human Behavior in Fire tend to move towards the Virtual Reality field will be discussed. VR experiments excel in many aspects over other research methods due to they provide experimental control, flexibility for the definition of experimental settings and data collection and others. Kinateder et al (2014) performed a SWOT (Strengths, Weaknesses, Opportunities and Threats) analysis where it is shown that strengths and opportunities of VR in HBiF overcome the possible Weaknesses and Threats. It is presented in Table 2.

Table 2. Summary of a SWOT Analysis for VR in Fire Evacuation Research. Taken from (Kinateder et al, 2014)

Strengths	Weaknesses	Opportunities	Threats
• Internal validity • Replication • Ecological validity • External validity • Safety for participants • Real-time feedback • Multi-modal simulations • Precise measurement • Psychophysiological monitoring • Low costs • Repeated measurements • Flexibility • Control of confounding variables • Independent of imagination abilities/willingness of participants • Participant recruitment	• Need for confirmation / validation • Non-intuitive interaction methods • Inter-individual differences in ease of interaction with VR • Technical limitations • Technology-induced side effects • Efforts	• Intuitive and natural navigation • Graphical developments • Multi-modal simulation and feedback • Usability for researchers • Exchange of 3D-scenes or experiments	• Failure to show ecological validity • Ethical challenges • Side-effects due to interaction with other medical conditions • Misleading expectations • Technical faults

Subjected to continuous changes and evolution, and not taking into account the fact that Virtual Reality for Human Behavior in Fire is still under discussion, VR technology provides a wide range of options available for researchers. A comparison among different technologies is suggested in order to help researchers in taking decisions on which of them to use. This issue is considered as the basis for proposing the goals of this project.

2.2 Theory of Affordances

Based on Gibson's (1977), (1986) studies on visual perception, Hartson (2003) defines the usefulness of concepts called affordances in the context of interaction design and evaluation. The called Theory of Affordances has widely assisted the analysis of the design of evacuation systems due to it provides guidelines to help designers in their will to increase the usability of, for instance, emergency systems.

An affordance is perceived in relation to what it offers or affords the individual (Gibson, 1986). An affordance is, hence, what the object offers the individual in relation to his or her goal (Ronchi & Nilsson, 2015). In this project the goal of individuals is to reach a safe place, therefore when studying about evacuation on tunnels it would be required to have a look at the affordances of emergency exit systems.

Ronchi and Nilsson (2014) intended to assist road tunnel safety designers and operators in the assessment of the appropriate emergency systems in the case of road tunnel evacuation by preforming a qualitative system evaluation using the Theory of Affordances. Suitable solutions for the design of emergency exit portals were identified and used as premise in the creation of a Theory of Affordances-based questionnaire (used in the base experiment and the one used in the present work.)

With the purpose of analyzing the possible affordances present in an evacuation system it is required to group them in types of affordances. Hartson (2003) categorizes four different types of affordances and tries to expand its definitions. They are presented below and keywords are added in order to give a first approach to them.

- Sensory affordance: Sensing or seeing
- Cognitive affordance: understanding
- Physical affordance: physically doing or using
- Functional affordance: fulfilment of the user's goal

It has been argued that the Theory of Affordances can be a useful tool for identifying potential design faults of evacuation systems early in the design process (Nilsson, 2009). By systematically exploring all the previously mentioned affordances of an evacuation system it should be possible, not only to determine optimal designs but, to identify conflictive and non-optimal ones (Ronchi & Nilsson, 2015).

The Theory of Affordances was used in original CAVE experiment and its understanding is key for the analysis of the results obtained. For this reason, the next sections are intended to provide more information regarding each type of affordances and the conflicts that might be present between them. For further explanation refer to Ronchi and Nilsson (2015).

2.2.1 Sensory affordance

If an individual has a goal, he/she has to first realize the means he/she has available in order to reach this goal, i.e. he/she has to sense these means. These means can be particular features that, once sensed, they have to provide sufficient information to catch the individual's attention. The details of these features have to be explicit. They should contrast the rest of the surrounding elements.

2.2.2 Cognitive affordance

This affordance supports the understanding of the observed means that were mentioned before (Nilsson, 2009). If these means are not correctly understood it can lead the user not to correctly use them or even not to reach the goal he/she was aiming. Therefore, the design features have to be consistent and well-considered. The designer has to take into consideration that the cognitive affordance goes in line with individual's previous experiences and preferences (Ronchi & Nilsson, 2015).

The cognitive affordances provided by a specific design can also be influenced by the context or nature of the situation. The message conveyed can have different meanings depending on the perspective of the individual.

2.2.3 Physical affordance

Physical affordance supports the individual when performing a physical action, i.e., it is certainly not a physical obstruction when trying to reach the goal. The user is physically meant to use the means given to reach the goal in a straightforward way and its design should be easy to operate.

2.2.4 Functional affordance

It helps or aids the user to achieve the desired goal (Hartson, 2003). The functional affordance can be seen as the final result from the balance and combination of sensory, cognitive and physical affordances. In other words, a functional affordance is appropriate when the individual can easy notice the means (sensory), completely understand its purpose (cognitive) and physically use them (physical).

2.2.5 Conflicting affordances

If the means are designed inappropriately, it can provide affordances that are in conflict with each other. It is very convenient to understand and spot the conflicting affordances when evaluating if a system is improperly designed.

2.2.6 Affordances in Emergency evacuation systems

The study of affordances have widely assisted the analysis of the design of evacuation systems since they can guide the designers in their will to increase the usability of, for instance, emergency exits. In an evacuation system it is highly recommended that the information is properly conveyed to the final user. This information should be transferred in a simple and understandable way regardless of its nature, for instance the location of an undesired event or routes the evacuees are not meant to use. This information should be easily distinguished.

Form a Sensory affordance point of view, Nilsson (2009) proposes introducing alternating patterns in the designs in order to increase people's attention, e.g., flashing lights for visual systems. Furthermore, it has been demonstrated that green color in emergency exit sings cognitively provides a feeling of safety to evacuees (Troncoso, 2014). As well, the way and difficulty opening a door in an emergency exit is a physical affordance that has to be constantly taken into account. Finally, functional affordance is provided in emergency evacuation systems when, for instance, an emergency exit portal is easy to notice (sensory), it has a purpose that is easy to understand (cognitive) and it physically possible to use it (Ronchi & Nilsson, 2015).

3 The Virtual Reality experiment

The experiments performed required several phases. These phases can be mainly grouped into three categories:

- preliminary work,
- experimental sessions and
- data analysis.

This section provides details of the first two phases by describing all the aspects taken into account by the researcher so that the third one can be accurately developed in the upcoming ones.

3.1 Preliminary work

Due to experiments for two different projects were done simultaneously, preliminary work had to be independently done in order to correctly organize a sequence to share the participants and create a smooth flow between them.

3.1.1 Software Used

Different Software and Software Developer Kits (SDK) were used in order to build a final android application (.APK). They are listed below.

- Windows 10 software:
  - Unity™ 5.4.2f2 (64-bit) and patches,
  - Monodevelop (IDE),
  - Android Studio™ 2.3: Android SDK,
  - Java™ 8 Update 121 (64-bit): JDK,
  - Oculus Mobile SDK,
  - SketchUp™ Make 2017,
  - Blender™ 2.78c (64-bit).
- Gear VR software for Samsung Galaxy S7 Edge:
  - Gear VR Service,
  - Gear VR System,
  - Samsung Gallery,
  - Samsung VR,
  - Oculus System Driver,
  - Oculus System Activities,
  - Oculus,
  - Oculus Home,
  - Unity Remote 5.

Additional configurations also were made in the mobile device such as switching it to Developer mode and Set up its signature file which was used in the Unity project for VR.

It is also important to mention that the statistical analysis of the results were done using the tools provided by IBM SPSS Build 1.0.0.355 (64-bit edition).

3.1.2 Hardware in use

The following devices were used during both, the preliminary work and the experimental sessions:

- Samsung Galaxy S7 Edge,
- Laptop Dell Intel® Core™ i7-5500U CPU @ 2.40GHz, 8.00 GB,
- Samsung Gear VR (2nd Generation),
- Xbox One Bluetooth 3.0 Controller,
- Glide VR Bluetooth 3.0 Controller.

3.1.3 Building the Android application

Virtual Reality scenarios for this project were created using the previously exposed programming and design tools. The overall VR environment consists mainly in a portion of a road tunnel based on the design of the Stockholm bypass Project (E4 The Stockholm bypass Project, 2015). Tunnel occupants were requested to navigate the VR environment with the final goal to reach a safe place which can be an emergency exit and also rate different designs. The VR environment was already constructed in a previous experiment (Ronchi & Nilsson, 2015). Adaptations such as changes in the materials, shaders or textures and simplifications such as removal of small unnoticed elements were made in order to make this VR project run in an Android mobile device without affecting the initial Virtual Environment. This VE consisted on the tunnel, cars, emergency lights, exit signage, traffic information signs, scripts for interactions player-VE, etc. Figure 6 shows the organization of the applications created and Figure 7 a general view of the VR tunnel scenario.

Figure 6. Mobile device screenshot showing the applications used and developed for the experiment.

Figure 7. Virtual Environment of the tunnel with Android build settings created in the game engine Unity.

3.2 The experiment

The experiment was carried out between 08:00 and 19:00 from March 22nd until March 30th in an office located in the third floor of the Physics Building 'E' at Lund University. Participants were contacted through various communication media and eventually booked a session of their preference.

3.2.1 Scenarios under consideration

Taking into account that 50 to 60 participants were initially expected to be tested, the experiments were carried out in a total of nine days with an average of seven participants per day. Each one at time was evaluated regarding way-finding (Part #1) and exit portals design (Part #2). The second part of this experiment contained six different scenarios which were presented to the participants in an alternated way so that they can evaluate them. Table 3 describes the scenarios (installation setups) used for this corresponding evaluation.

Table 3. List of installation setups. Taken from (Ronchi & Nilsson, 2015). The cells in green color correspond to the installation setups (with its corresponding scenario name) chosen to be analyzed in the present project.[3]

Scenario name*	**Variable under investigation**	**Color**	**Flashing Rate**	**Type of light source**	**Layout and position**
RS	Color	Green	1 Hz	LED	3 lights
C1		White	1 Hz	LED	3 lights
C2		Blue	1 Hz	LED	3 lights
FR1	Flashing Rate	Green	4 Hz	LED	3 lights
RS		Green	1 Hz	LED	3 lights
FR2		Green	0.25 Hz	LED	3 lights
TL1	Type of light source	Green	1 Hz	Strobe	3 lights
RS		Green	1 Hz	LED	3 lights
TL2		Green	1 Hz	Double strobe	3 lights
LP1	Layout and position	Green	1 Hz	LED	2 Bars
RS		Green	1 Hz	LED	3 lights
LP2		Green	1 Hz	LED	1 light
NO	No lights	/	/	/	/
E (Extra)	Door design with painted running man	Green	1 Hz	LED	3 lights

** Legend: RS = Reference Scenario, CX = Color (1 or 2), FRX = Flashing rate (1 or 2), TLX = Type of lights (1 or 2), LP = Light position (1 or 2), NO = No lights, E = Extra scenario. Gray colored cells group the scenarios according to their variable under investigation.*

The selection of the scenarios to be used in this project was done through analyzing the previous results of their descriptive/inferential statistical results. To aid this selection, the emergency exit designs that varied the most and the ones that resemble the most to a reference chosen design were taking into account. More details about these designs are presented in Table 4 and Figure 8.

[3] The choice of these installations setups was made taking into considerations factors such as number of participants, time available and principally the statistical results that each setup provided in the base experiment.

Table 4. Details of chosen installation setups.

Scenario name	Characteristics
RS	Reference scenario (green lights, 1 Hz flashing rate, LED lights, 3 lights)
C2	Blue lights
FR1	Fast flashing
TL1	Single Strobe
LP1	2 bars
NO	No lights

Figure 8. VR emergency exit portal designs. a. Reference scenario (Fast flashing and Single Strobe designs look the same but present variances in the flashing rate and period correspondingly), b. Blue lights, c. 2 bars and d. No lights.

3.2.2 Experimental procedure

The experiment for this project was divided in two main parts preceded by a rapid training one. During the training part, participants were requested to try the gamepad and get familiar with the navigation system by dodging obstacles and crossing rooms and doors. During Part #1, participants navigated in the VR tunnel and they were requested to navigate the environment with the final goal to reach a safe place, e.g. an emergency exit. In Part #2, participants stood in front of six different exit portal configurations and ranked them through a questionnaire.

Five groups (eleven participants each) took part in every experimental setup. An experimental setup is a group of scenarios ordered in a particular way so that they differ from one another in order to avoid systematic errors or learning factors. The assignation of participants to these groups was made according to the day they chose in the previously mentioned Doodle. No particular distinction or arrangement was made regarding mobility or extra safety precautions due to all of the participants were expected to be regular students.

Figure 9 presents a flowchart that schematizes the different parts of the experimental session, Figure 10 illustrates the time taken per part. Note that both figures include information regarding VR experiments for a different project that was being performed parallel. Figure 11 provides further details regarding the experiment for this project.

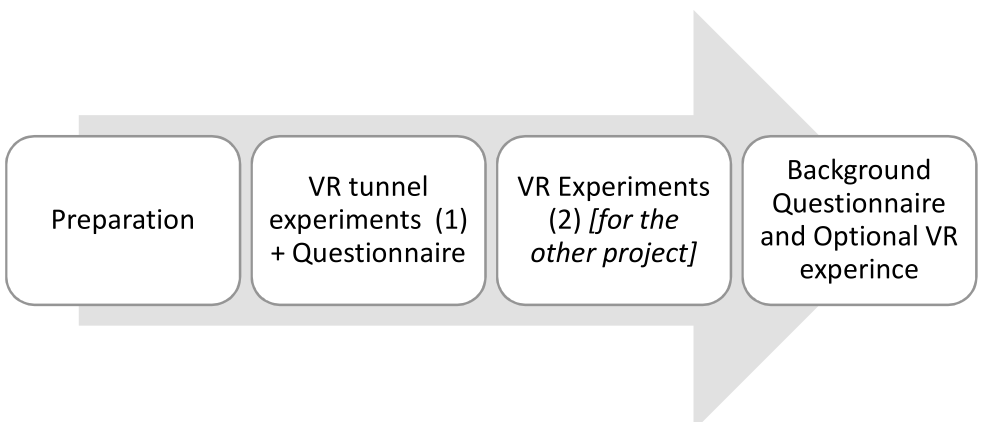


Figure 9. Flow chart of the experiment session.

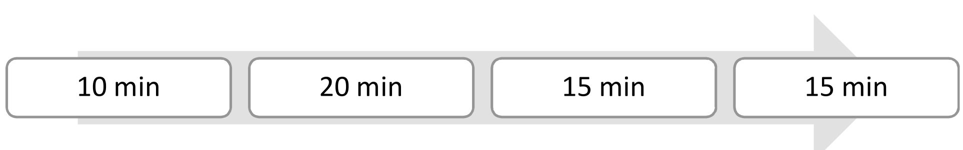


Figure 10. Time-line of the experiment session.

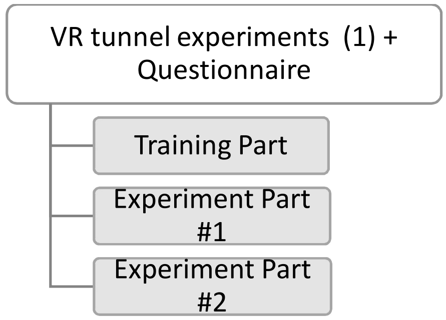


Figure 11. Experiment parts.

All participants were asked to experience all the parts of the experimental session and it was also mentioned to them that they had the right to abort the experiment at any time by telling any of the Researches present in the laboratory. An informed consent form that was read and signed by each participant can be found in Appendix D

3.2.2.1 Training Part

With the purpose of getting familiar with the navigation system in the VR environments, the participants were first requested to move around a Test scenario. This scenario has no link to the tunnel evacuation scenario and no data will be registered from it.

VR Scenario:

The scenario consists on a corridor with obstacles and doors. Participants were required to navigate and freely move through it for a few seconds, cross two doors and reach a final room when they felt comfortable with the navigation.

Figure 12. Navigation Test scenario.

3.2.2.2 Experiment Part #1

After the Test scenario was done, the tunnel scenario took place. Participants were be requested to navigate the Virtual Environment and find their way out to a safe place. Due to the installation setup of the scenario in this part of the experiment was the same as the one proposed for the base experiment no significant changes were made to it (see Figure 7).

VR Scenarios:

The initial position of the participant corresponded to a middle point between two emergency exit doors (specifically next to the driver door of a car, see Figure 13). Both exits (green lines in Figure 13) are separated 100 m (in accordance with the Stockholm bypass project). Participants were asked to find their way out of the tunnel by reaching a safe place. This part of the experiment finished when the participants either reached one of the exits mentioned before or they reach a certain distance considered to be the end of the tunnel (blue lines in Figure 13). The total length of the VR scenario is 200 m and it contains a curve at each end of the tunnel as illustrated in Figure 14.

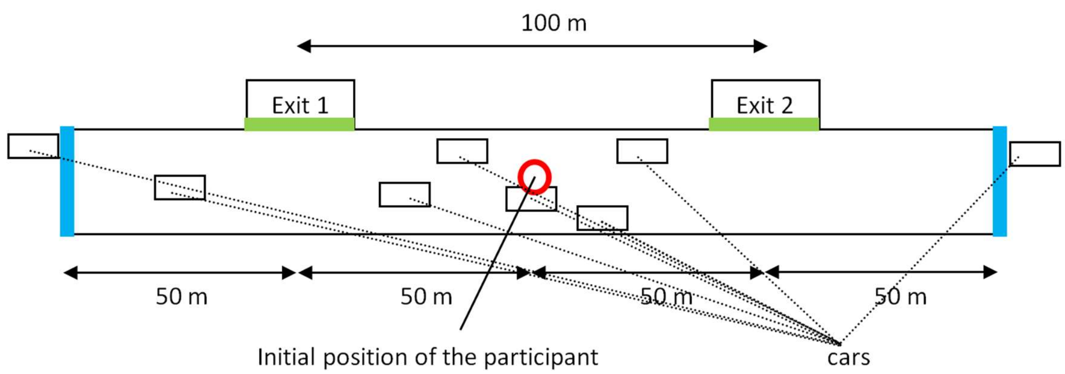


Figure 13. Schematic layout of the tunnel during experiment Part #1. The elements within the tunnel (cars, exits, etc.) are off scale to facilitate the reading of the figure. Figure taken from (Ronchi & Nilsson, 2015)

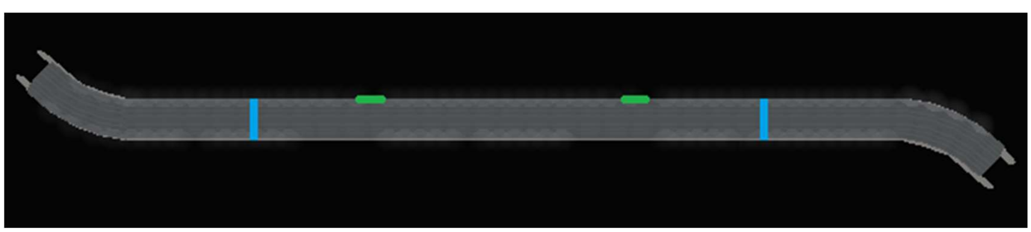


Figure 14. Schematic representation of the full Virtual Environment. Green lines indicates emergency exits (off-scale to facilitate the reading of the figure) and blue lines indicates the end of the scenarios. Figure taken from (Ronchi & Nilsson, 2015)

The scenario was terminated if one of five possible conditions occur, i.e. if a participant reached one of the four targets (green and blue lines) or if he/she did not find any of them within a fixed amount of time. The four targets are the two emergency exits (green lines in Figure 14) and the areas that are more than 50 m past the exits in one of the two sides (blue lines in Figure 14). The last condition is the case of a participant not reaching any target within 5 minutes (the scenario is automatically terminated when the time expired). Participants' movement path was recorded at each time-step (0.5 s). The time to reach one of the target areas was also recorded. (Ronchi & Nilsson, 2015)

Each one of the five groups of participants had a different baseline scenario for this part of the experiment. It mainly differed in the design of the exit portals (specifically the features of the flashing lights). In order to have a clearer appreciation, Table 5 presents the configurations fixed for each group.

Table 5. Emergency exit configurations in Part #1 depending on the group of participants.

Scenario name	VR Scenario	Color	Flashing Rate	Type of light source	Layout and position	Number of participants	Group
RS	1A	Green	1 Hz	LED	3 lights	11	1
C2	1C	Blue	1 Hz	LED	3 lights	11	2
FR1	2A	Green	4 Hz	LED	3 lights	11	3
TL1	3A	Green	1 Hz	Strobe	3 lights	11	4
LP1	4A	Green	1 Hz	LED	2 Bars	11	5

3.2.2.3 Experiment Part #2

Once the baseline tunnel evacuation scenario was completed, the participant was directed to the part where different exit portals designs were evaluated. Participants were initially placed at a certain distance and angle from each exit portal configuration (adjusted according to (Ronchi & Nilsson, A Virtual Reality experiment on the design of flashing lights at emergency exit portals for road tunnel evacuations, 2015)). A few seconds were given to them in order to analyze the design and after that three questions per configuration were asked and their responses where annotated in an online form (see Appendix B). As it can be observed in this appendix, each participant was asked to rank six different configurations using a seven points Likert scale (from -3 to +3, where -3 is the worst and +3 is the best) by answering 3 questions based on the Theory of Affordances. There was also the possibility that participants provide an open comment at the end of the experiment.

VR Scenarios:

Each participant was requested to rank six different exit portals configurations. The order in which these configurations were presented differed in order to avoid systematic errors. To accomplish this, the first design administered corresponded to the baseline design in Part #1 of the experiment and the following ones were chosen in a randomized order. Table 6 presents the order of the scenarios for each group of participants.

Table 6. Randomization of the configurations for Part #2 of the experiment.

Group	Number of particip.	Part #1 Scenario	Part #2 Scenarios (in order)					
1	10	RS	RS	C1	NO	FR1	TL1	LP1
2	10	C1	C1	TL1	NO	RS	FR1	LP1
3	10	FR1	FR1	LP1	NO	C1	TL1	RS
4	10	TL1	TL1	RS	NO	FR1	LP1	C1
5	10	LP1	LP1	C1	NO	TL1	RS	FR1

It is important to note that unlike the base experiment (Ronchi & Nilsson, 2015), fatigue control by using repeated configurations at the beginning and end of Part #2 was not used in this project due to no significant impact was revealed in the previous study.

3.3 Participants

A total of fifty five (55) participants were part of the experiment (29 female and 26 male). Participant's age varied from 20 to 37 years old (resulting into an average value of 25.11 years and a standard deviation of 3.99 years). Five participants (9.1%) had Swedish nationality and the rest 90.9% where from 33 different nationalities from six different continents. Most of the participants were living in Sweden under temporary basis due to studies. Fifty four (98.18%) of the participants corresponded to a mixture of Bachelor, Master and PhD students. Only one participant mentioned to present sight impairments ("Slight red-green distinguishing difficulty") and many of them were able to use their own glasses when using the headset.

A single participant mentioned to have a previous experience of an emergency in a road tunnel. The case corresponded to a car accident in a tunnel in Kosovo and the participant used an emergency exit. Most of the participants (43 out of 55, i.e., 78.20%) had a driving license. A considerable portion of the participants corresponded to frequent users of tunnels (40% of the sample if combining once a month, once a week and everyday tunnel users), fourteen participants (25.50%) expressed to be once a year users and nineteen of them (34.50%) were less frequent than once a year users.

Despite almost one quarter of the sample (13 participants, i.e. 23.6%) stated to have very small experience in videogames, it can be said that generally participants have somehow an idea of videogames due to six (10.90%) mentioned to have a very large experience, ten (18.20%) large experience, eighteen (32.70%) regular experience and eight (14.50%) small experience. The majority of the participants declared not to have any experience with VR experiments before. One participant mentioned to have been part of a campaign about facing fears with VR for high altitudes and another one expressed previous experience concerning evacuations in Virtual Reality. He specifically mentioned the fact that he has tried before the CAVE system used for the base experiment of this project.

All participants were contacted through social networks and email. Indications regarding experiment's location, research topics, procedures and risks were mentioned in advance. A doodle tool was used so that they could choose a time slot during the weeks when the experiments took place. Reminders were constantly sent in order to maintain the desired order.

Figure 15. Participant navigating the VR tunnel in Part #1

Figure 16. Participant answering to questions in Part #2.

4 Experimental results

This section is divided in two parts. The first one corresponds to the presentation data obtained in the path tracking of Part #1 and the one collected through the questionnaire in Part #2. Eventually, the second subsection offers a comparison between the results obtained in both experiments.

4.1 Results

Part #1 provided information regarding participants' pathfinding. Figure 17 illustrates the path followed by all participants in the evacuation from the Road tunnel scenario.

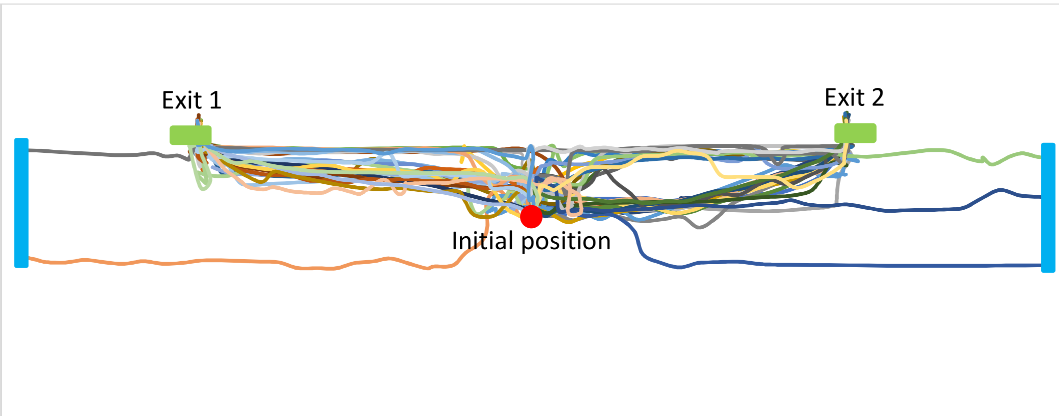


Figure 17. Tracked paths of the participants.

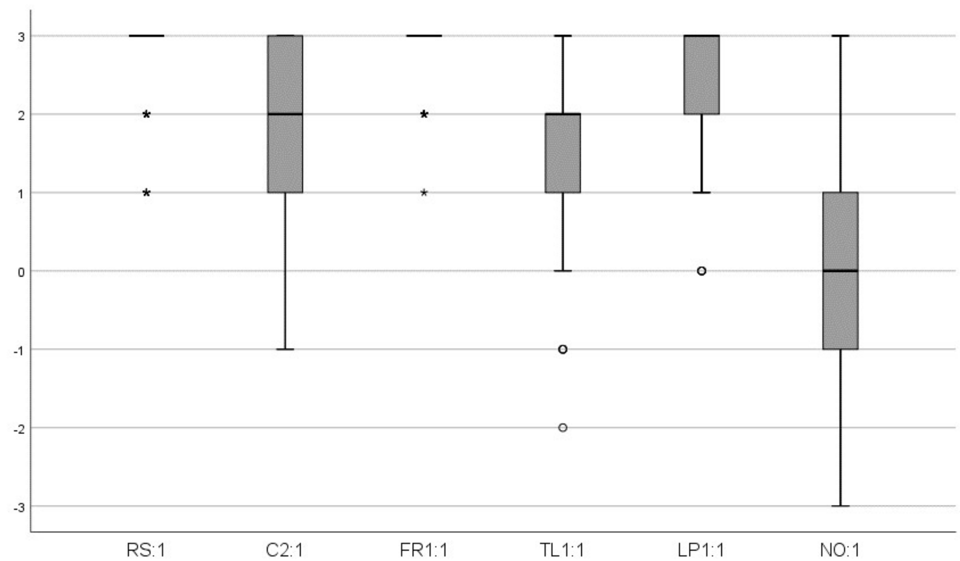
It can be observed that fifty participants (90.91%) reached one of the Emergency exits. By analyzing the steps and time taken, it can be said that the other five participants continued their way until reaching the end of the tunnel scenario. The possible reasons for this behavior will be discussed in the discussion section.

The results obtained in Part #2 are presented as descriptive statistics. Likert-scale responses to Questions 1, 2 and 3 asked per emergency exit design (Appendix B) are shown in Table 7 and Figure 18 for Sensory affordance (Question 1), Table 8 and Figure 19 for Cognitive affordance (Question 2) and Table 9 and Figure 20 for Functional affordance (Question 3).

Table 7. Descriptive statistics of the responses to Question 1 on Sensory affordance.

Scenario	Description	N	Mean	∑ (St. dev.)	Min	Max	Percentiles		
							25th	50th (Median)	75th
RS:1	Reference	55	2.67	0.64	1	3	3	3	3
C2:1	Blue Lights	55	1.75	1.09	-1	3	1	2	3
FR1:1	Fast flashing	55	2.80	0.45	1	3	3	3	3
TL1:1	Single Strobe	55	1.62	1.18	-2	3	1	2	2
LP1:1	2 bars	55	2.35	0.89	0	3	2	3	3
NO:1	No lights	55	-0.07	1.64	-3	3	-1	0	1

(-3 and +3 represent the minimum and maximum scores correspondingly. The code ':1' refers to Question 1)



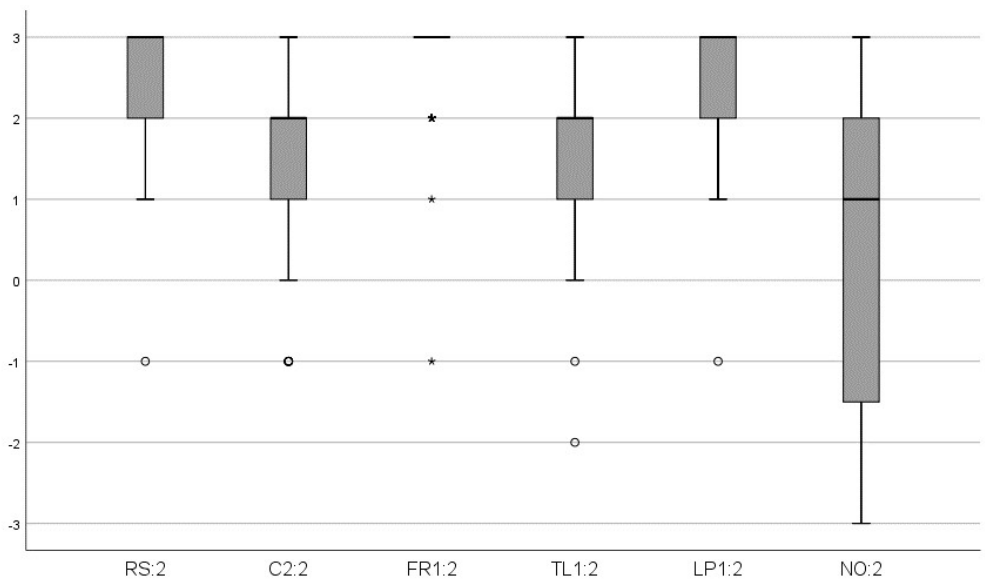
(-3 and +3 represent the minimum and maximum scores correspondingly. The code ':1' refers to Question 1)

Figure 18. Boxplots of the responses to Question 1 on Sensory affordance.

Table 8. Descriptive statistics of the responses to Question 2 on Cognitive affordance.

Scenario	Description	N	Mean	∑ (St. dev.)	Min	Max	Percentiles		
							25th	50th (Median)	75th
RS:2	Reference	55	2.51	0.84	-1	3	2	3	3
C2:2	Blue Lights	55	1.56	1.18	-1	3	1	2	2
FR1:2	Fast flashing	55	2.71	0.69	-1	3	3	3	3
TL1:2	Single Strobe	55	1.71	1.10	-2	3	1	2	2
LP1:2	2 bars	55	2.35	0.84	-1	3	2	3	3
NO:2	No lights	55	0.18	1.89	-3	3	-2	1	2

(-3 and +3 represent the minimum and maximum scores correspondingly. The code ':2' refers to Question 2)



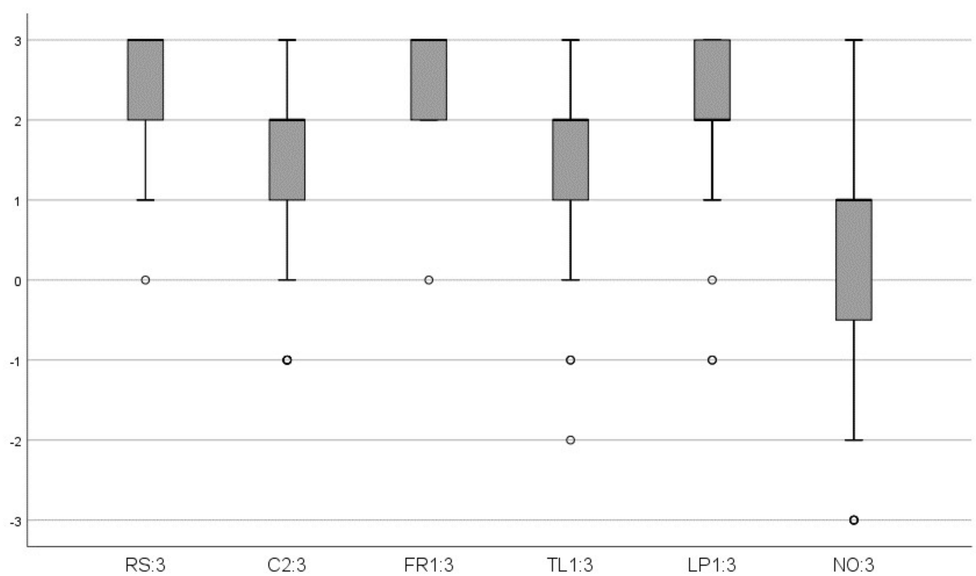
(-3 and +3 represent the minimum and maximum scores correspondingly. The code ':2' refers to Question 2)

Figure 19. Boxplots of the responses to Question 2 on Cognitive affordance.

Table 9. Descriptive statistics of the responses to Question 3 on Functional affordance.

Scenario	Description	N	Mean	Σ (St. dev.)	Min	Max	Percentiles		
							25th	50th (Median)	75th
RS:3	Reference	55	2.40	0.76	0	3	2	3	3
C2:3	Blue Lights	55	1.58	1.13	-1	3	1	2	2
FR1:3	Fast flashing	55	2.69	0.57	0	3	2	3	3
TL1:3	Single Strobe	55	1.58	1.03	-2	3	1	2	2
LP1:3	2 bars	55	2.18	0.92	-1	3	2	2	3
NO:3	No lights	55	0.29	1.66	-3	3	-1	1	1

(-3 and +3 represent the minimum and maximum scores correspondingly. The code ':3' refers to Question 3)



(-3 and +3 represent the minimum and maximum scores correspondingly. The code ':1' refers to Question 1)

Figure 20. Boxplots of the responses to Question 3 on Functional affordance.

The data expressed in the three previous tables (Table 7, Table 8 and Table 9) can already provide information regarding the differences between the Emergency exit designs. Percentiles, means and standard deviations are scalar data that in a quantitative approach could be used to present a ranking among the designs. However, an ordinal model is used to study the results (ideal for Likert scale results management) and investigate through inferential statistics if the differences between the designs are statistically significant.

Initially, the first two affordances (Sensory and Cognitive – corresponding to Question 1 and 2 of Part #2) are subjected to a Wilcoxon signed-rank test in order to identify if the scores of the different door designs are statistically different. It is important to note that it is established that the RS design is considered to be a reference point to evaluate the rest of the designs. This RS presents features that has not only been validated as precise but it also represents a reference in the base experiment. The results of the test are presented in Table 10 and Table 11.

Table 10. Results of the Wilcoxon signed-rank test for Sensory affordance.

	C2:1 - RS:1	FR1:1 - RS:1	TL1:1 - RS:1	LP1:1 - RS:1	NO:1 - RS:1
Z	-4.754[a]	-1.380[b]	-5.164[a]	-2.145[a]	-6.306[a]
Asymp. Sig. (2-tailed)	0.000	0.167	0.000	0.032	0.000

a. Based on positive ranks.
b. Based on negative ranks.
Scenarios that resulted to be statistically different from the reference one are shown in gray.

Table 11. Results of the Wilcoxon signed-rank test for Cognitive affordance.

	C2:2 - RS:2	FR1:2 - RS:2	TL1:2 - RS:2	LP1:2 - RS:2	NO:2 - RS:2
Z	-4.737[a]	-1.947[b]	-4.306[a]	-1.372[a]	-5.831[a]
Asymp. Sig. (2-tailed)	0.000	0.052	0.000	0.17	0.000

a. Based on positive ranks.
b. Based on negative ranks.
Scenarios that resulted to be statistically different from the reference one are shown in gray.

In order to detect statistically different designs, a significance level of 5% is commonly used ($\alpha = 0.05$). Nevertheless, due to the fact that the Wilcoxon test was applied to multiple comparisons a Bonferroni correction is applied to the results, i.e. the significance level is divided by the number of comparisons (5 designs) and a new corrected value is obtained ($\alpha_c = 0.01$).

Considering the new significance level, the designs that are considered statistically different to the preferred referential scenario RS are those presented in gray color in Table 10. The study of the Sensory affordance sets that these scenarios are C2 (blue lights), TL1 (single strobe) and NO (no lights) due to they present a significance level below the one settled after the Bonferroni correction. The results for the Cognitive affordance are presented in Table 11 and they are qualitatively similar to the ones presented before. The statistically different designs are also C2, TL1 and NO.

From the results obtained in Table 7, Table 8 and Table 9, it can be qualitatively argued that there is a proportional relation between Functional affordance and both, Sensory and Cognitive. This correlation can be drawn from the descriptive statistics presented in the tables. This premise leads to the following sections where the scores provided by the participants are analyzed, compared and discussed.

A Wilcoxon test was also performed for the Functional affordance (Question 3 of Part #2) in order to compare the scores obtained among the different door configurations. The comparisons of these various two-related-samples test are presented in Table 12 and the statistics in Table 13.

Table 12. Paired comparisons of all the scenarios for Question 3 on Functional affordance.

Comparison		**N**	**Mean Rank**	**Sum of Ranks**
Reference vs blue lights (C2:3 vs RS:3)	Negative Ranks	30	19.6	588
	Positive Ranks	6	13	78
	Ties	19	-	-
	Total	55	-	-
Reference vs fast flashing (RS:3 vs FR1:3)	Negative Ranks	2	8.5	17
	Positive Ranks	16	9.63	154
	Ties	37	-	-
	Total	55	-	-
Reference vs single (RS:3 vs TL1:3)	Negative Ranks	31	17.27	535.5
	Positive Ranks	3	19.83	59.5
	Ties	21	-	-
	Total	55	-	-
Reference vs 2 bars (RS:3 vs LP1:3)	Negative Ranks	19	16.95	322
	Positive Ranks	12	14.5	174
	Ties	24	-	-
	Total	55	-	-
Reference vs no lights (RS:3 vs NO:3)	Negative Ranks	44	24.25	1067
	Positive Ranks	2	7	14
	Ties	9	-	-
	Total	55	-	-

Table 13. Results of the Wilcoxon signed-rank test for Functional affordance.

	C2:3 - RS:3	FR1:3 - RS:3[4]	TL1:3 - RS:3	LP1:3 - RS:3	NO:3 - RS:3
Z	-4.103[a]	-3.258[b]	-4.172[a]	-1.597[a]	-5.788[a]
Asymp. Sig. (2-tailed)	0.000	0.001	0.000	0.110	0.000

a. Based on positive ranks.
b. Based on negative ranks.
Scenarios that resulted to be statistically different from the reference one are shown in gray.

Taking into account the previously mentioned Bonferroni correction used for the significance level to define if the scores to the designs are statistically different, the results on the Functional affordance show that the designs that differ from the reference one (RS) are: C2 (blue lights), FR1 (fast flashing), TL1 (single strobe) and NO (no lights). The results of these designs express the fact that they have a higher proportion of lower scores than the reference design RS. Notice that in this particular affordance, the design FR1 turns to be statistically different. This result was not expected in the sense that it did not show any indication neither in the analysis of the previous affordances nor in the base experiment. Further discussion will be held in the discussion section.

Table 14 displays a summary of the results for all questions and all the different designs. It is important to note that in an overall way, the scenarios that do not statistically differ from the referential one are FR1 (fast flashing) and LP1 (2 bars). These results are completely aligned with the descriptive statistics presented in Table 7, Table 8 and Table 9, where the lowest mean scores were obtained by the statistically different designs, i.e. $\mu < 1.76$.

Table 14. Summary of the results of the Wilcoxon tests for all affordances.

Scenario comparison	Scenario under consideration	Sensory	Cognitive	Functional
C2 - RS	Blue lights	≠	≠	≠
FR1 - RS	Fast flashing	=	=	≠
TL1 - RS	Single Strobe	≠	≠	≠
LP1 - RS	2 bars	=	=	=
NO - RS	No lights	≠	≠	≠

[4] This paired comparison is the only one that returned different results when compared to the ones gotten from the previous experiment.

4.2 Comparison with the previous experiment

A starting point at the moment of drawing comparisons is provided by Figure 21. The differences in required equipment are shown in the shape of a Venn diagram where the common hardware components are presented in the middle space.

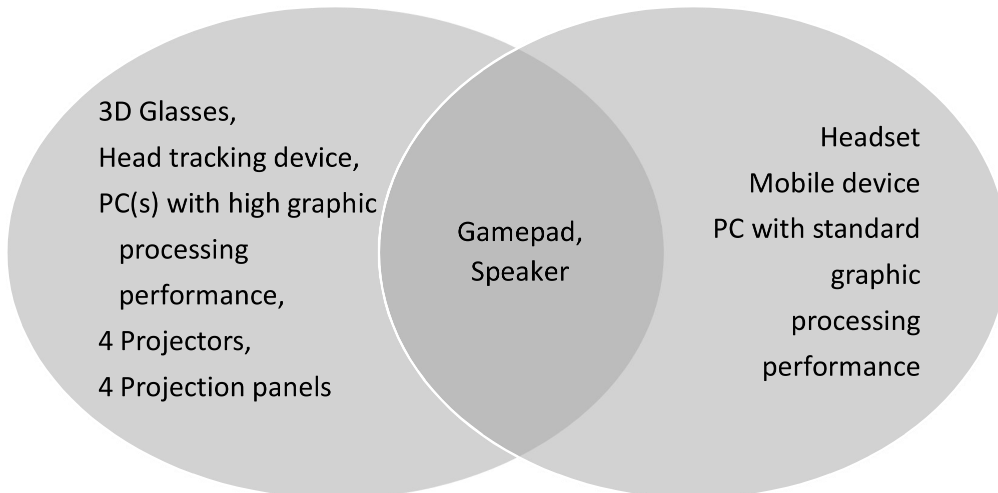


Figure 21. Comparison of the hardware required for both experiments.

A vital and guiding aspect through the whole preliminary work is a visual inspection between the Virtual Environment of the experiment done in this project and the one previously performed by Ronchi and Nilsson (2015). Figure 22 displays this comparison.

Figure 23 presents the trajectories followed by participants in the base experiment. Figure 24 corresponds to the trajectories for the present experiment. It is important to note that five of the trajectories have been omitted from this graph due to its final destination was not the region of interest (any of the emergency exits). Further discussion will be held in the corresponding section.

Figure 22. Visual comparison of the Virtual Environments. a. VE visualization in the previous experiment. Taken from Lovreglio, Ronchi and Nilsson (2015). b. Screenshot of the VE for the present experiment.

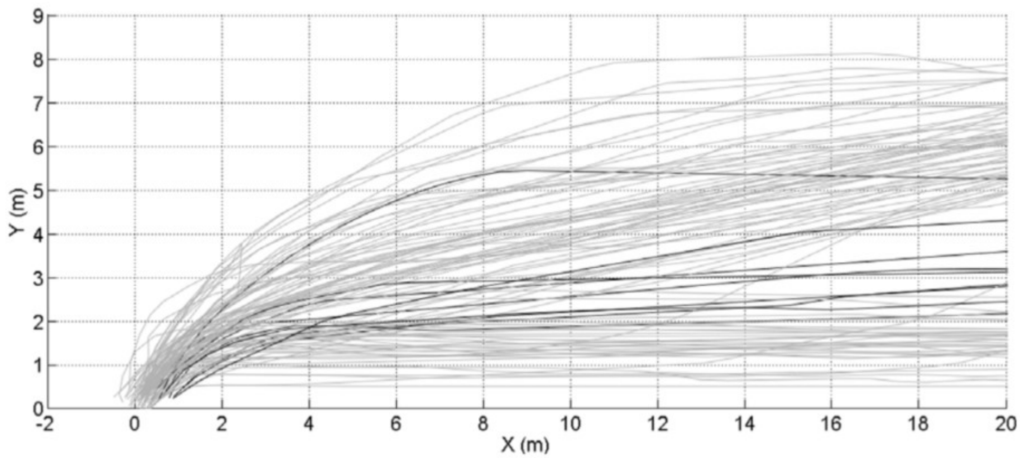
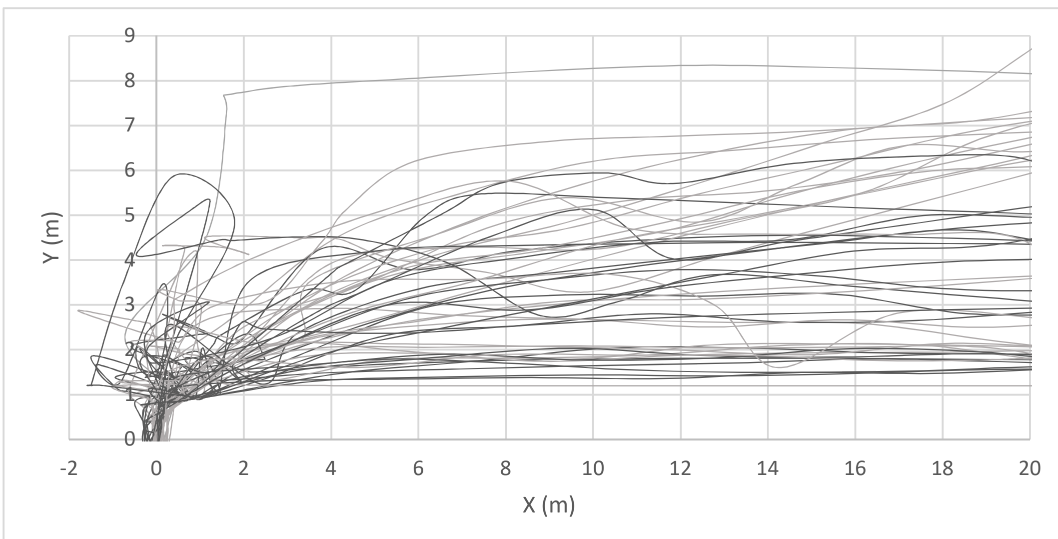


Figure 23. Trajectories of the 96 participants of the base experiment (Ronchi & Nilsson, 2015) in the merged region of interest. Taken from Lovreglio, Ronchi and Nilssoon (2015).



(The trajectories of 25 participants (black lines) reaching Exit 1 are mirrored and overlapped to those of the remaining 25 participants (gray lines). The trajectories are plotted in a local system of reference ('X' parallel to longitudinal axis of the tunnel, 'Y' orthogonal to longitudinal axis of the tunnel) having origin center of the exit. All measures are expressed in meters)

Figure 24. Trajectories of 50 participants in the merged region of interest.

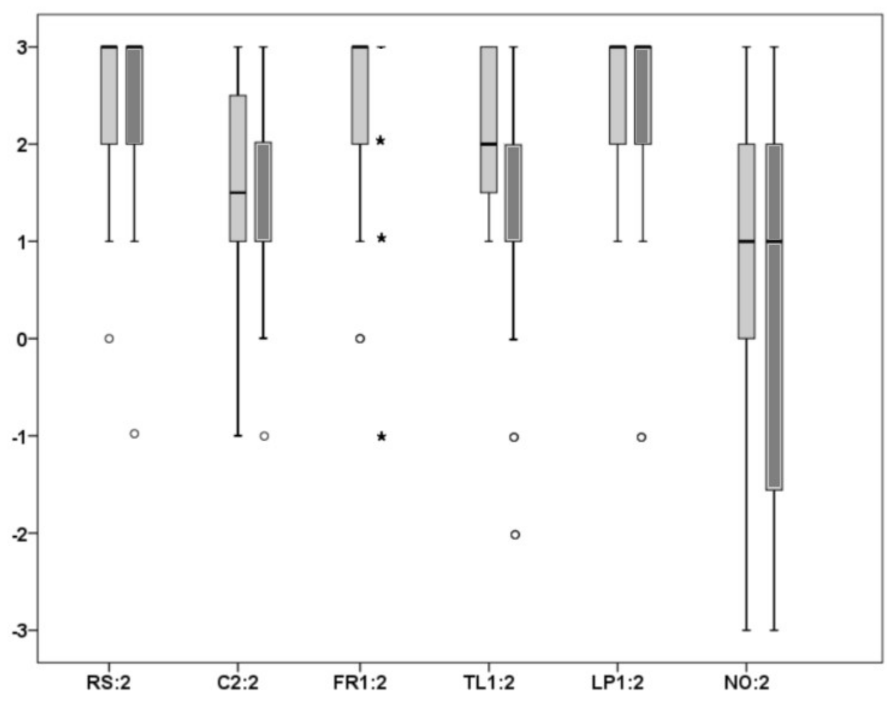
The ranking of the emergency exit portals regarding each one of the affordances (Sensory, Cognitive and Functional) was obtained from the Questions on Part #2 and expressed in tables showing descriptive statistics. Table 15 reflects a comparison between the results obtained to Question 1 on Sensory affordance for the experiments. (The figures in clear gray show the results obtained in the experiment performed by Ronchi and Nilsson)

Figure 25 displays the comparison for the boxplots created with the answers to Question 2 on Cognitive affordance for both experiments.

Table 15. Comparison of the descriptive statistics of the responses to Question 1 on Sensory affordance for both experiments.

Scen.	Desc.	N		Mean		Σ (St. dev.)		Min		Max		Percentiles					
												25th		50th		75th	
RS:1	Reference	96	55	2.74	2.67	0.44	0.64	2	1	3	3	2	3	3	3	3	3
C2:1	Blue Lights	48	55	1.21	1.75	1.07	1.09	-1	-1	3	3	0	1	1	2	2	3
FR1:1	Fast flashing	48	55	2.77	2.80	0.43	0.45	2	1	3	3	3	3	3	3	3	3
TL1:1	Single Strobe	48	55	1.94	1.62	0.76	1.18	0	-2	3	3	2	1	2	2	2	2
LP1:1	2 bars	48	55	2.71	2.35	0.50	0.89	1	0	3	3	2	2	3	3	3	3
NO:1	No lights	96	55	0.31	-0.07	1.23	1.64	-3	-3	3	3	-1	-1	1	0	1	1

-3 and +3 represent the minimum and maximum scores correspondingly. The code ':1' refers to Question 1)
(Data in gray represents the results obtained in the experiment performed by Ronchi and Nilsson (2015))



(The figures in clear gray show the results obtained in the experiment performed by Ronchi and Nilsson (2015))

Figure 25. Comparison of the boxplots of the responses to Question 2 on Cognitive affordance for both experiments. Adapted from Ronchi and Nilsson (2015)

With the purpose of determining differences in the ranking given to the exit portal designs inferential statistics were used to investigate if the designs are statistically different. Sets of a Wilcoxon signed-rank test were done using a Reference Scenario RS. Table 16 presents the comparison between the results obtained to Question 3 on Functional affordance for both experiments.

Table 16. Comparison of the results of the Wilcoxon signed-rank test for Functional affordance for both experiments.

	C2:3 - RS:3		**FR1:3 - RS:3**		**TL1:3 - RS:3**	
Z	-4.979[a]	-4.103[a]	-0.393[b]	-3.258[b]	-3.976[a]	-4.172[a]
Asymp. Sig. (2-tailed)	0.000	0.000	0.694	0.001	0.000	0.000
	LP1:3 - RS:3		**NO:3 - RS:3**			
Z	-1.387[a]	-1.597[a]	-8.061[a]	-5.788[a]		
Asymp. Sig. (2-tailed	0.166	0.110	0.000	0.000		

a. Based on positive ranks.
b. Based on negative ranks.
(Data in gray represents the results obtained in the experiment performed by Ronchi and Nilsson (2015))

The conclusions drawn from the results of the Wilcoxon test done to all the questions regarding the affordances were tabulated in a way that it is shown if each design is statistically different to the reference one in every affordance. Table 17 presents the comparison between the summary for both experiments.

Table 17. Comparison of the Summaries of the results of the Wilcoxon tests for all affordances for both experiments.

Scenario comparison	**Scenario under consideration**	**Sensory**		**Cognitive**		**Functional**	
C2 - RS	Blue lights	≠	≠	≠	≠	≠	≠
FR1 - RS	Fast flashing	=	=	=	=	=	≠
TL1 - RS	Single Strobe	≠	≠	≠	≠	≠	≠
LP1 - RS	2 bars	=	=	=	=	=	=
NO - RS	No lights	≠	≠	≠	≠	≠	≠

5 Discussion and Conclusions

Based on general observations, the tracking paths of the participants and the responses to the affordance-based questionnaire of the present experiment, and additionally on the comparison with the previous experimental work done by Ronchi and Nilsson (2015) this study provides cross comparison validation between experiments done with a CAVE system and a HMD powered by a mobile device. A comparison was made and reasonable levels of resemblance were detected in the results of both experiments.

The preliminary work required to build a VR environment for both platforms departs from a CAD design and eventually the game engine Unity permits to simply build the project for any of the technologies with minor changes and settings.

The hardware required for the present work implies not only less equipment but also less expensive tools than the one used for the previous experiment. The fact that the present work is dedicated to low-cost Head Mounted Displays and that the experiment could be replicated provides a pre-validation before analyzing the results.

A visual comparison showed that graphical results obtained with both technologies are similar after applying variations to materials, shaders, textures and lighting. Nevertheless, restrictions and problems were faced regarding performance (specifically frame rate delays due to renderization of enormous quantities of polygons). The correct management of sounds using applications developed with Unity for Samsung Gear VR also has limitations and in this experiment it was required to reproduce them through an external speaker.

When comparing the trajectories followed by the participants in Part #1, a smoother and more direct path is observed in the experiment developed by Ronchi and Nilsson (2015). The swing trajectories found in this experiment are assumed to happen due to the limited time given to participants in the testing scenario where they got familiar with the navigation system or due to the fact that most of them initially know that the researcher could not see what they do and, since it was the first VR experience for many, they opted to explore. The navigation velocity was kept the same compared to the previous experiment. Nevertheless, only in Part #1, due to rendering delay caused by the mobile device performance, a great amount of participants expressed their desire to move faster (like in a videogame) and in their attempt to do so it is assumed that their trajectory was disturbed. Another possible reason can be attributed to VR sickness. A condition similar to motion sickness that a VE can cause. Several participants expressed having slightly experienced it during the testing part which preceded the navigation in the tunnel in Part #1.

All questions were analyzed with descriptive statistics where percentiles, maximum, minimum and mean values were calculated. All these previous values, including the corresponding standard deviation and a graphical representation of the results through boxplots, presented slight variances between both experiments. Therefore it can be argued that the comparison provided a positive outcome and the results obtained in the experiment performed for this project justify the usage of low-cost Head Mounted Displays as a research tool in Human Behavior in Fire.

The previous argument gains strength when inferential statistics through a Wilcoxon signed-rank test also present almost no variance. The results obtained in the current experiment are 93.33% similar to the ones obtained in the previous experiment (only one out of fifteen pair comparisons presented opposite statistical difference status). The design which presented different results is the one where the flashing rate was modified. It was previously stated that a rendering delay was observed but this delay was not present in Part #2 (from where the data was obtained to perform the statistical analysis). Therefore, despite it is a fact that the flashing frequency can be perceived differently depending on the HMDs performance, the variation in these results are not completely attributed to this statement but to a comprehensible variation between experiments.

Despite the results of the present experiment turned to be the same as the ones previously obtained by Ronchi and Nilsson (2015), it should also be discussed the impact that the sample of this experiment has (this can be a possible source of uncertainty and the reason why some results varied). The most particular fact is that the sample was mainly composed by international students whose mother tongue was not generally English (language used for this experiment). This can be an extra cause why five participants did not use an emergency exit in Part #1 (possible misunderstanding of the statement). The majority of the sample under consideration in this study possessed a driving license and had limited tunnel usage and tunnel evacuation experience and, as Ronchi and Nilsson (2015) did in line with the findings of Gandit (2009), a generalization of results for able-bodied adults will be allowed. Also it is important to note that no generalization is made for people with sight impairments due to only one participants confirmed to have them.

Ronchi and Nilsson (2015), supported by the findings of Galea et al. (2013), expressed their concern regarding the fact that colors regarding evacuation may have different meanings in different cultures. The present study can be used as first step to reduce this barrier, i.e., the statement that the color constrain compromises the global application of the results found in this study can be now questioned. From the perception of the author of this study, it is a fact that emergency exit signs in many countries are written mainly in red (E.g. western countries). Nevertheless, there is a trend in most of these countries to move from red color to green when referring to emergency exit signs. Previous studies have also corroborated that green is the color of preference despite the different connotations this might have from culture to culture (Troncoso, 2014). Participants from Caribbean, Central and South America (regions with mainly red emergency exit designs) had no difficulties in using the exits or rank them.

To conclude, the present study provides stronger support to Virtual Reality using Head Mounted Displays as a research method due to the cost-effectiveness, agreement in results with other VR methods and the easiness of obtainment of a great quantity of data in a relatively short time (55 participants provided 576 individual observations that generated 1728 measurements). HMDs are systems that can provide results comparable to the ones obtained by more robust and expensive technologies.

6 Recommendations for future work

The discussion regarding the advantages and difficulties when performing experiments in HBiF using Virtual Reality with HMDs powered by mobile devices provided positive comments regarding the usage of this technology as a research tool. Nevertheless, several recommendations are given in order to improve robustness and friendliness method.

The level of immersion for both experiments can be improved by adding extra features to the Virtual Environment. Smoke production can be included not only by particles systems (Unity game engine objects) but by using pre-calculated Computational Fluid Dynamics (CFD) tools such as FDS (Fire Dynamics Simulator) (Xu, Kim, Lee, Ki, & Lee, 2013). Background sound and radiation sources could also increase the sensation of being present in the environment. To include interaction with objects was highly suggested by the participants who mentioned that it will add more realism to the experiment.

As mentioned, simplifications and changes in the Virtual Environment were done. All these with the purpose of creating a softer version in terms of graphics performance so that the processor of the mobile device can run it. This phase introduced most of the limitations and resulted to be the most time consuming phase of the project. Therefore, it is recommended the usage of Head Mounted Displays powered by a PC if the Virtual Environment requires an increased level of complexity.

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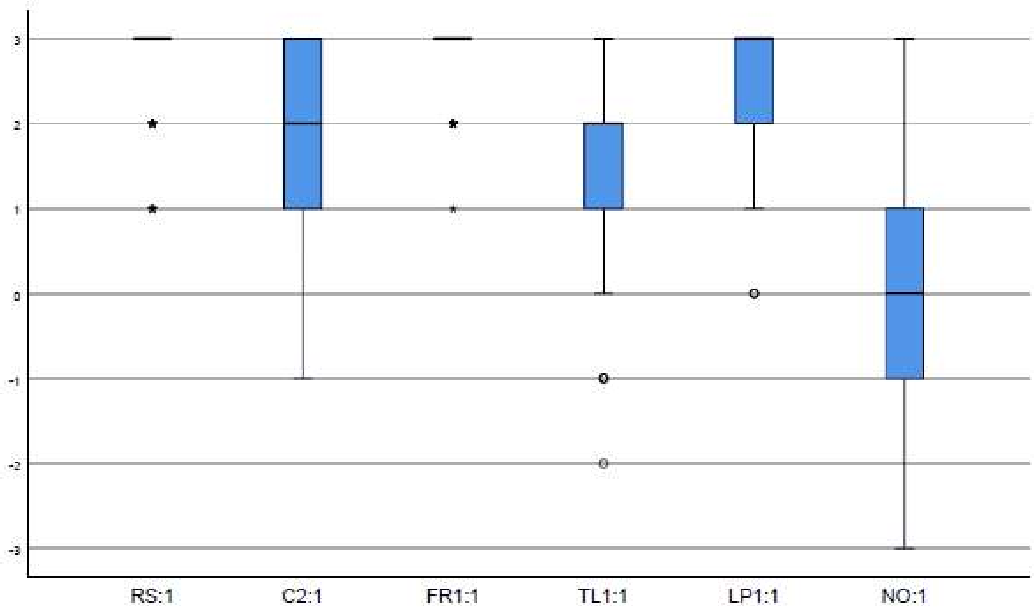
Appendices

Appendix A: SPSS statistics

Statistical Results 1. Simple boxplots definition process for responses to Question 1 on Sensory affordance.

Case Processing Summary

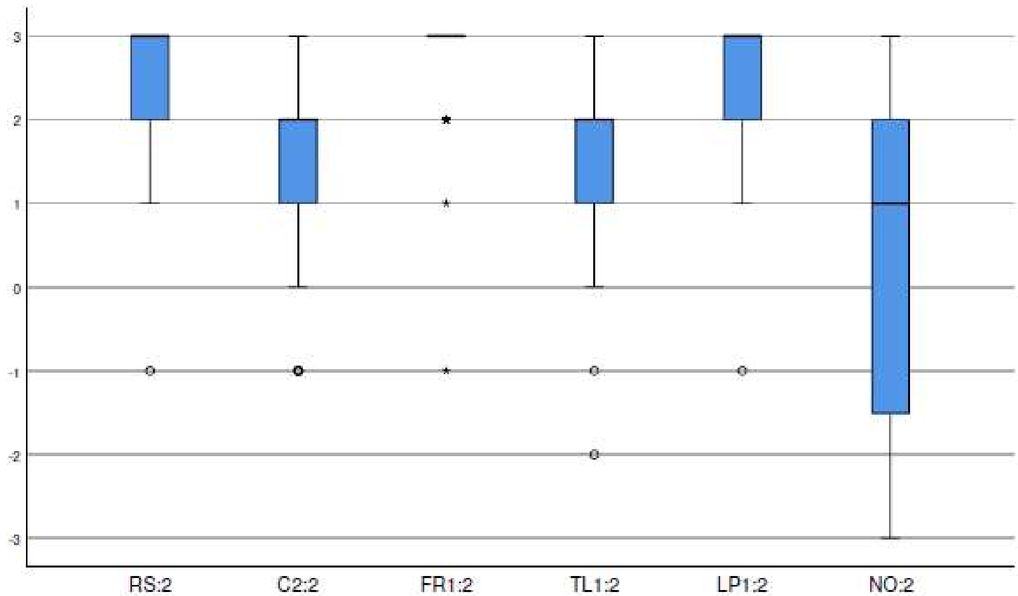
	Cases					
	Valid		Missing		Total	
	N	Percent	N	Percent	N	Percent
RS:1	55	100.0%	0	0.0%	55	100.0%
C2:1	55	100.0%	0	0.0%	55	100.0%
FR1:1	55	100.0%	0	0.0%	55	100.0%
TL1:1	55	100.0%	0	0.0%	55	100.0%
LP1:1	55	100.0%	0	0.0%	55	100.0%
NO:1	55	100.0%	0	0.0%	55	100.0%



Statistical Results 2. Simple boxplots definition process for responses to Question 2 on Cognitive affordance.

Case Processing Summary

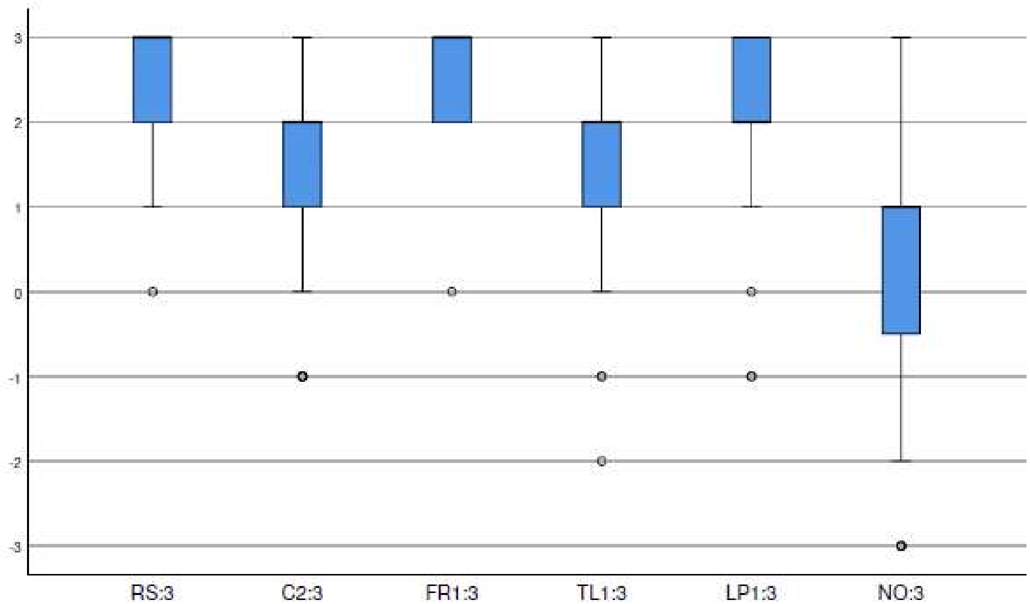
	Cases					
	Valid		Missing		Total	
	N	Percent	N	Percent	N	Percent
RS:2	55	100.0%	0	0.0%	55	100.0%
C2:2	55	100.0%	0	0.0%	55	100.0%
FR1:2	55	100.0%	0	0.0%	55	100.0%
TL1:2	55	100.0%	0	0.0%	55	100.0%
LP1:2	55	100.0%	0	0.0%	55	100.0%
NO:2	55	100.0%	0	0.0%	55	100.0%



Statistical Results 3. Simple boxplots definition process for responses to Question 3 on Functional affordance

Case Processing Summary

	Cases					
	Valid		Missing		Total	
	N	Percent	N	Percent	N	Percent
RS:3	55	100.0%	0	0.0%	55	100.0%
C2:3	55	100.0%	0	0.0%	55	100.0%
FR1:3	55	100.0%	0	0.0%	55	100.0%
TL1:3	55	100.0%	0	0.0%	55	100.0%
LP1:3	55	100.0%	0	0.0%	55	100.0%
NO:3	55	100.0%	0	0.0%	55	100.0%



Statistical Results 4. Two-Related Samples Tests (Wilcoxon type) for Question 1.

NPar Tests

Descriptive Statistics

	N	Mean	Std. Deviation	Minimum	Maximum	Percentiles 25th	50th (Median)	75th
RS:1	55	2.67	.640	1	3	3.00	3.00	3.00
C2:1	55	1.75	1.092	-1	3	1.00	2.00	3.00
FR1:1	55	2.80	.447	1	3	3.00	3.00	3.00
TL1:1	55	1.62	1.178	-2	3	1.00	2.00	2.00
LP1:1	55	2.35	.886	0	3	2.00	3.00	3.00
NO:1	55	-.07	1.643	-3	3	-1.00	.00	1.00

Wilcoxon Signed Ranks Test

Ranks

		N	Mean Rank	Sum of Ranks
C2:1 - RS:1	Negative Ranks	32[a]	18.66	597.00
	Positive Ranks	3[b]	11.00	33.00
	Ties	20[c]		
	Total	55		
FR1:1 - RS:1	Negative Ranks	5[d]	8.60	43.00
	Positive Ranks	11[e]	8.45	93.00
	Ties	39[f]		
	Total	55		
TL1:1 - RS:1	Negative Ranks	37[g]	21.19	784.00
	Positive Ranks	3[h]	12.00	36.00
	Ties	15[i]		
	Total	55		
LP1:1 - RS:1	Negative Ranks	19[j]	12.61	239.50
	Positive Ranks	6[k]	14.25	85.50
	Ties	30[l]		
	Total	55		
NO:1 - RS:1	Negative Ranks	52[m]	27.38	1424.00
	Positive Ranks	1[n]	7.00	7.00
	Ties	2[o]		
	Total	55		

a. C2:1 < RS:1
b. C2:1 > RS:1
c. C2:1 = RS:1
d. FR1:1 < RS:1
e. FR1:1 > RS:1
f. FR1:1 = RS:1
g. TL1:1 < RS:1
h. TL1:1 > RS:1
i. TL1:1 = RS:1
j. LP1:1 < RS:1
k. LP1:1 > RS:1
l. LP1:1 = RS:1
m. NO:1 < RS:1
n. NO:1 > RS:1
o. NO:1 = RS:1

Test Statistics[a]

	C2:1 - RS:1	FR1:1 - RS:1	TL1:1 - RS:1	LP1:1 - RS:1	NO:1 - RS:1
Z	-4.754[b]	-1.380[c]	-5.164[b]	-2.145[b]	-6.306[b]
Asymp. Sig. (2-tailed)	.000	.167	.000	.032	.000

a. Wilcoxon Signed Ranks Test

b. Based on positive ranks.

c. Based on negative ranks.

Statistical Results 5. Two-Related Samples Tests (Wilcoxon type) for Question 2.

NPar Tests

Descriptive Statistics

	N	Mean	Std. Deviation	Minimum	Maximum	Percentiles		
						25th	50th (Median)	75th
RS:2	55	2.51	.836	-1	3	2.00	3.00	3.00
C2:2	55	1.56	1.183	-1	3	1.00	2.00	2.00
FR1:2	55	2.71	.685	-1	3	3.00	3.00	3.00
TL1:2	55	1.71	1.100	-2	3	1.00	2.00	2.00
LP1:2	55	2.35	.844	-1	3	2.00	3.00	3.00
NO:2	55	.18	1.887	-3	3	-2.00	1.00	2.00

Wilcoxon Signed Ranks Test

Ranks

		N	Mean Rank	Sum of Ranks
C2:2 - RS:2	Negative Ranks	36[a]	20.89	752.00
	Positive Ranks	4[b]	17.00	68.00
	Ties	15[c]		
	Total	55		
FR1:2 - RS:2	Negative Ranks	5[d]	9.90	49.50
	Positive Ranks	14[e]	10.04	140.50
	Ties	36[f]		
	Total	55		
TL1:2 - RS:2	Negative Ranks	31[g]	18.39	570.00
	Positive Ranks	4[h]	15.00	60.00
	Ties	20[i]		
	Total	55		
LP1:2 - RS:2	Negative Ranks	18[j]	12.58	226.50
	Positive Ranks	8[k]	15.56	124.50
	Ties	29[l]		
	Total	55		
NO:2 - RS:2	Negative Ranks	47[m]	25.43	1195.00
	Positive Ranks	2[n]	15.00	30.00
	Ties	6[o]		
	Total	55		

a. C2:1 < RS:1
b. C2:1 > RS:1
c. C2:1 = RS:1
d. FR1:1 < RS:1
e. FR1:1 > RS:1
f. FR1:1 = RS:1
g. TL1:1 < RS:1
h. TL1:1 > RS:1
i. TL1:1 = RS:1
j. LP1:1 < RS:1
k. LP1:1 > RS:1
l. LP1:1 = RS:1
m. NO:1 < RS:1
n. NO:1 > RS:1
o. NO:1 = RS:1

Test Statistics[a]

	C2:2 - RS:2	FR1:2 - RS:2	TL1:2 - RS:2	LP1:2 - RS:2	NO:2 - RS:2
Z	-4.737[b]	-1.947[c]	-4.306[b]	-1.372[b]	-5.831[b]
Asymp. Sig. (2-tailed)	.000	.052	.000	.170	.000

a. Wilcoxon Signed Ranks Test
b. Based on positive ranks.
c. Based on negative ranks.

Statistical Results 6. Two-Related Samples Tests (Wilcoxon type) for Question 3.

NPar Tests

Descriptive Statistics

	N	Mean	Std. Deviation	Minimum	Maximum	Percentiles 25th	50th (Median)	75th
RS:3	55	2.40	.760	0	3	2.00	3.00	3.00
C2:3	55	1.58	1.134	-1	3	1.00	2.00	2.00
FR1:3	55	2.69	.573	0	3	2.00	3.00	3.00
TL1:3	55	1.58	1.031	-2	3	1.00	2.00	2.00
LP1:3	55	2.18	.925	-1	3	2.00	2.00	3.00
NO:3	55	.29	1.663	-3	3	-1.00	1.00	1.00

Wilcoxon Signed Ranks Test

Ranks

		N	Mean Rank	Sum of Ranks
C2:3 - RS:3	Negative Ranks	30[a]	19.60	588.00
	Positive Ranks	6[b]	13.00	78.00
	Ties	19[c]		
	Total	55		
FR1:3 - RS:3	Negative Ranks	2[d]	8.50	17.00
	Positive Ranks	16[e]	9.63	154.00
	Ties	37[f]		
	Total	55		
TL1:3 - RS:3	Negative Ranks	31[g]	17.27	535.50
	Positive Ranks	3[h]	19.83	59.50
	Ties	21[i]		
	Total	55		
LP1:3 - RS:3	Negative Ranks	19[j]	16.95	322.00
	Positive Ranks	12[k]	14.50	174.00
	Ties	24[l]		
	Total	55		
NO:3 - RS:3	Negative Ranks	44[m]	24.25	1067.00
	Positive Ranks	2[n]	7.00	14.00
	Ties	9[o]		
	Total	55		

a. C2:1 < RS:1
b. C2:1 > RS:1
c. C2:1 = RS:1
d. FR1:1 < RS:1
e. FR1:1 > RS:1
f. FR1:1 = RS:1
g. TL1:1 < RS:1
h. TL1:1 > RS:1
i. TL1:1 = RS:1
j. LP1:1 < RS:1
k. LP1:1 > RS:1
l. LP1:1 = RS:1
m. NO:1 < RS:1
n. NO:1 > RS:1
o. NO:1 = RS:1

Test Statistics[a]

	C2:3 - RS:3	FR1:3 - RS:3	TL1:3 - RS:3	LP1:3 - RS:3	NO:3 - RS:3
Z	-4.103[b]	-3.258[c]	-4.172[b]	-1.597[b]	-5.788[b]
Asymp. Sig. (2-tailed)	.000	.001	.000	.110	.000

a. Wilcoxon Signed Ranks Test

b. Based on positive ranks.

c. Based on negative ranks.

Appendix B: Background of participants

Appendix Table 1. Participant's background information.

Name and Last Name	Age	Nationality	Gender	In which country do you live?	Are you color blind?	What is your main occupation?	Do you have a driving license?	How often do you drive in road tunnels?	Do you have any previous experience of an emergency in a road tunnel?	How much experience do you already have in computer games?	Have you participated before as a volunteer in an evacuation with Virtual Reality?
Felix Hård	22	Swedish	Male	Sweden	No	Programmer	No	Less frequent than once a year	No	Large	No
Ioanna Asimakopoulou	20	Greek	Female	Greece	No	Student	Yes	Less frequent than once a year	No	Very small	No
Claudio Mandrioli	23	Italian	Male	Sweden	No	Student	Yes	Once a month	No	Small	No
Juan Chaves	25	Colombian	Male	Sweden	No	Student	Yes	Once a week	No	Something in between	No
Alejandra Velasco	25	Salvadorian	Female	Sweden	No	Student	Yes	Less frequent than once a year	No	Something in between	No
Nicolas Alvear	25	Chilean	Male	Sweden	No	Student	Yes	Once a month	No	Very large	No
Sandra Yousif	24	Swedish	Female	Sweden	No	Student	Yes	Less frequent than once a year	No	Small	No
Ming-Cian Hong	34	Taiwanese	Male	Sweden	No	Student	Yes	Once a year	No	Large	No
Sergio Vargas	25	Costa Rican	Male	Sweden	No	Student	Yes	Once a year	No	Very small	No
Nanami Zuzuki	20	Japanese	Female	Sweden	No	Student	Yes	Less frequent than once a year	No	Very small	No
Kanako Yasuoka	21	Japanese	Female	Sweden	No	Student	Yes	Once a year	No	Something in between	No
Zulfiya Gafurova	23	Uzbek	Female	Sweden	No	Student	No	Once a week	No	Very small	No
Christoffer Huynh	25	Swedish	Male	Sweden	No	Student	No	Less frequent than once a year	No	Very large	No
Sawsan Kanaan	21	Jordanian	Female	Sweden	No	Student	Yes	Every day	No	Very small	No
Marius Herr	24	German	Male	Sweden	No	Student	Yes	Less frequent than once a year	No	Something in between	No

Name and Last Name	Age	Nationality	Gender	In which country do you live?	Are you color blind?	What is your main occupation?	Do you have a driving license?	How often do you drive in road tunnels?	Do you have any previous experience of an emergency in a road tunnel?	How much experience do you already have in computer games?	Have you participated before as a volunteer in an evacuation with Virtual Reality?
Friday Shen	22	Chinese	Female	Sweden	No	Student	No	Less frequent than once a year	No	Something in between	No
Sara Al Twassi	22	Jordanian	Female	Sweden	No	Student	Yes	Once a week	No	Something in between	No
Kunsulu Bekish	23	Kazakh	Female	Sweden	No	Student	No	Once a month	No	Very small	No
Guangqi Qin	30	Chinese	Male	Sweden	No	Student	Yes	Once a year	No	Something in between	No
Yunan Zhou	27	Chinese	Female	Sweden	No	Student	Yes	Once a year	No	Very small	No
Rohan John Baptiste	37	St. Lucian	Male	Sweden	No	Student	Yes	Less frequent than once a year	No	Something in between	No
Maria Dimou	20	Greek	Female	Sweden	No	Student	No	Less frequent than once a year	No	Something in between	No
Júlia Coelho Trojan	24	Brazilian	Female	Sweden	No	Student	Yes	Once a month	No	Small	No
Werner Nystrand	33	Swedish	Male	Sweden	No	Student	Yes	Once a month	No	Very large	No
Fiona de Heer	25	Irish	Female	Sweden	No	Student	Yes	Less frequent than once a year	No	Large	No
Monica Carpio	31	Costa Rican	Female	Sweden	No	Student	Yes	Less frequent than once a year	No	Very small	No
Blaise Bayuo	31	Ghanaian	Male	Sweden	No	Student	No	Once a year	No	Large	No
Katie Abbott	22	British	Female	Sweden	No	Student	Yes	Once a month	No	Very small	No
Ettore Carini	28	Italian	Male	Sweden	No	Student	Yes	Once a year	No	Large	Yes
Banne Matutu	27	Indonesian	Female	Sweden	No	Student	Yes	Less frequent than once a year	No	Very large	No
Saar Hoek	21	Dutch	Female	Sweden	No	Student	Yes	Once a year	No	Something in between	No
Zhi Min Lin	20	Australian	Male	Sweden	Yes	Student	Yes	Once a year	No	Very large	No
Evin Thana	30	Kosovar	Female	Sweden	No	Student	Yes	Less frequent than once a year	Yes	Something in between	No
Sylvia Platteeuw	26	Dutch	Female	Sweden	No	Student	Yes	Once a year	No	Very small	No

Name and Last Name	Age	Nationality	Gender	In which country do you live?	Are you color blind?	What is your main occupation?	Do you have a driving license?	How often do you drive in road tunnels?	Do you have any previous experience of an emergency in a road tunnel?	How much experience do you already have in computer games?	Have you participated before as a volunteer in an evacuation with Virtual Reality?
Habib Hamidy	30	Indonesian	Male	Sweden	No	Student	Yes	Once a month	No	Something in between	No
Arjan Dexters	28	Belgian	Male	Sweden	No	Student	Yes	Once a month	No	Large	No
Alexandra Platonova	21	Swedish	Female	Sweden	No	Student	No	Once a year	No	Very small	No
Israt Jahan Mukti	31	Bangladeshi	Female	Sweden	No	Student	No	Less frequent than once a year	No	Something in between	No
AKM Fahmidul Haque	31	Bangladeshi	Male	Sweden	No	Student	No	Less frequent than once a year	No	Small	No
Mathieu Verpaele	24	Belgian	Male	Sweden	No	Student	Yes	Once a month	No	Large	No
Pingting Hu	24	Chinese	Female	Sweden	No	Student	Yes	Less frequent than once a year	No	Something in between	No
Ye Qian	25	Chinese	Female	Sweden	No	Student	Yes	Less frequent than once a year	No	Very small	No
Botir	20	Uzbek	Male	Sweden	No	Student	Yes	Every day	No	Small	No
Murodilla Rikhsiboev	22	Uzbek	Male	Sweden	No	Student	Yes	Once a month	No	Large	No
Darko Perovic	25	Serbian	Male	Sweden	No	Student	Yes	Once a month	No	Large	No
Sanjin Bajramovic	27	Bosnia and Herzegovina	Male	Sweden	No	Student	Yes	Once a week	No	Something in between	No
Nina Nesterova	22	Russian	Female	Sweden	No	Student	Yes	Once a year	No	Very small	No
Carlos Arellano	27	Ecuadorian	Male	Sweden	No	Student	No	Less frequent than once a year	No	Very large	No
Melchior Schepers	24	Belgian	Male	Sweden	No	Student	Yes	Once a month	No	Something in between	No
Looi Khai Chern	26	Malaysian	Male	Sweden	No	Student	Yes	Once a year	No	Large	No
Natacha Askovic	20	French	Female	Sweden	No	Student	No	Once a month	No	Something in between	No
Cynthia Chauvet	20	French	Female	Sweden	No	Student	Yes	Once a month	No	Something in between	No
Martina Varisco	26	Italian	Female	Sweden	No	Student	Yes	Once a week	No	Small	No

Name and Last Name	Age	Nationality	Gender	In which country do you live?	Are you color blind?	What is your main occupation?	Do you have a driving license?	How often do you drive in road tunnels?	Do you have any previous experience of an emergency in a road tunnel?	How much experience do you already have in computer games?	Have you participated before as a volunteer in an evacuation with Virtual Reality?
Hicham Kouhkouh	23	Moroccan	Male	Sweden	No	Student	Yes	Once a year	No	Small	No
Martha Ålgård	29	Norwegian	Female	Sweden	No	Student	Yes	Once a month	No	Small	No

Appendix C: Questions and answers to Part #2

Each participant is asked to rank a total of 6 designs. Participants are asked to rank the designs answering 3 questions per configuration using a Likert scale (from -3 to +3). These questions are based on the Theory of Affordances.

- Q1: State on a scale from -3 to +3 how easy it is to discover the design.
- Q2: State on a scale from -3 to +3 how easy it is to understand that the design is an exit that you should use.
- Q3: State on a scale from -3 to +3 how good support the design offers for your evacuation.

Appendix Table 2. Answers to questions on the Theory of Affordances for each design in Part#2.

1A			1C			2A			3A			4A			NO		
Q1	**Q2**	**Q3**	**Q1**	**Q2**	**Q3**	**Q1**	**Q2**	**Q3**	**Q1**	**Q2**	**Q3**	**Q1**	**Q2**	**Q3**	**Q1**	**Q2**	**Q3**
3	3	2	2	3	2	3	3	3	0	2	2	2	2	2	-1	0	2
2	3	2	3	2	2	3	3	3	0	-2	-1	2	2	2	-3	-3	-3
1	3	2	0	1	1	3	3	3	-1	0	1	3	3	3	-2	-1	0
3	3	2	3	2	3	3	3	3	2	1	2	3	3	3	0	1	1
3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	2	3
3	3	3	1	1	0	3	3	3	1	2	1	3	3	3	-1	0	0
3	3	2	3	3	2	2	3	2	1	3	2	3	3	2	1	3	2
1	1	1	2	2	2	2	-1	2	-2	1	2	1	2	2	-2	2	1
3	3	1	3	3	2	3	3	3	3	3	3	2	3	2	1	3	2
2	2	3	2	2	2	3	3	3	1	2	1	1	1	1	-1	-2	-2
3	3	3	1	1	2	3	3	3	-1	1	2	3	3	3	-3	-2	1
3	3	3	-1	3	1	2	3	3	3	2	1	3	3	3	-2	-3	-2
3	2	3	2	1	0	3	3	3	-1	0	-1	0	1	-1	0	-3	-3
2	1	1	2	3	2	3	2	2	1	1	1	2	1	2	-1	1	0
1	3	2	1	2	2	3	3	2	2	2	1	3	2	2	0	0	0
3	3	3	2	2	2	3	3	3	1	2	1	2	2	2	0	1	1
2	1	3	1	-1	-1	3	3	3	1	2	2	3	2	2	-1	1	-1
1	1	0	1	0	2	2	2	2	2	2	2	0	-1	-1	2	3	1
3	3	3	3	2	2	3	3	3	3	2	1	2	2	2	3	1	0
3	2	3	2	2	3	3	3	3	1	2	1	2	1	2	1	0	1
3	3	3	3	2	2	3	3	3	3	1	2	1	1	2	-1	-1	1
3	3	3	2	2	3	3	3	3	2	2	3	3	3	3	1	2	3
3	2	3	2	1	2	3	3	3	2	1	2	3	3	3	2	1	2
3	3	3	3	2	3	3	2	3	3	3	3	3	2	3	2	2	3
3	3	3	3	3	3	3	3	3	1	2	2	3	3	3	2	2	2
3	2	2	2	1	-1	3	3	3	1	0	-2	3	3	3	1	2	0
3	3	1	3	3	1	3	3	0	1	2	0	3	3	2	0	-2	-2
3	3	3	3	1	1	3	3	3	2	2	2	3	3	3	0	-3	-3
3	3	2	2	2	2	3	3	2	3	3	2	3	3	2	2	3	2
3	2	2	1	0	1	2	2	3	2	-1	1	1	1	0	-3	-3	-2
3	3	3	1	2	1	3	3	3	2	3	2	3	3	3	0	1	0
3	3	2	3	1	2	3	3	2	3	3	2	3	2	2	2	2	2
3	3	3	2	2	2	3	3	3	3	3	3	3	3	3	-2	-2	-1
3	3	3	1	1	1	3	3	3	2	1	1	2	3	2	-1	0	0

1A			**1C**			**2A**			**3A**			**4A**			**NO**		
Q1	**Q2**	**Q3**	**Q1**	**Q2**	**Q3**	**Q1**	**Q2**	**Q3**	**Q1**	**Q2**	**Q3**	**Q1**	**Q2**	**Q3**	**Q1**	**Q2**	**Q3**
3	3	3	1	1	1	3	3	3	2	1	1	2	3	2	-1	0	0
3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	2	2
3	3	3	-1	2	1	3	3	2	1	2	1	1	3	2	-2	1	-1
3	2	1	2	1	-1	3	2	2	2	1	1	3	2	1	-1	1	-3
2	-1	1	1	-1	1	3	1	2	2	1	1	3	2	2	1	-2	0
3	3	3	2	2	2	3	3	3	3	3	3	2	2	2	2	2	2
3	3	3	2	3	3	3	3	3	2	3	2	3	2	2	1	1	1
3	1	2	1	0	1	3	2	2	2	1	1	3	3	3	0	0	0
3	3	3	3	2	3	3	3	3	3	2	3	3	3	3	3	2	3
2	2	2	1	2	2	2	2	2	1	2	2	2	2	2	1	1	1
1	1	2	2	2	3	2	3	2	2	2	2	3	3	3	-3	-3	1
3	3	3	3	3	3	3	3	3	3	3	3	2	2	2	1	-1	1
3	3	3	1	2	2	3	2	3	2	2	1	3	3	2	0	1	1
2	3	2	2	1	1	3	3	3	1	2	2	2	3	2	1	2	1
3	2	2	0	-1	-1	3	3	3	0	0	1	1	2	1	-2	-2	-2
3	3	3	-1	-1	2	3	3	3	2	2	2	2	2	2	-2	1	0
2	3	3	2	0	1	2	2	3	2	1	1	3	3	3	0	1	1
3	3	3	1	1	1	2	3	3	2	3	2	3	3	3	0	1	0
3	2	2	2	2	1	3	3	3	1	0	1	3	2	3	-2	-3	-2
3	2	2	2	3	2	3	3	3	1	2	2	2	3	3	1	0	1
3	3	2	0	-1	-1	1	2	2	2	2	2	0	1	1	-2	-3	-2

Appendix D: Informed consent document of the experiment

Lund University - IMFSE

This informed consent form is for students who are currently enrolled at Lund University and who are in invited to participate in research with Virtual Reality experiments.

Investigators: David Mayorga & Francisco Rosero
IMFSE- Lund University
Project 1: Flashing lights at road tunnel emergency exit portals: A Virtual Reality study with Head Mounted Displays
Project 2: Assessment of People's Perception of Fire Growth: A Virtual Reality Study

Information

The aim of these experiments is, perform a cross-validation between two different VR technologies using as method the replication of an experiment previously developed in an environment with flashing lights at emergency exit portals in road tunnels (Ronchi & Nilsson, 2015) and to evaluate how people perceived risk in a fire scenario represented in VR when compared with other training methods (e.g. educational videos).

The experiment set up was modelled in 3D software attempting to achieve a good level of realism to allow participants to be immersed in the experiments. The software Unity 3D was used to program the games and the logics of the virtual environments. As platforms "GEAR VR" and "Oculus Rift" will be used for the experiments. Participants will be immersed in virtual scenarios and navigate on them using an X-Box Controller. The research will take place in Lund University from March 22nd to March 30th , 2017 and will last approximately one hour. Your participation in this research is entirely voluntary. It is your choice whether to participate or not.

Procedure

The experiments will take place on the date previously schedule. Once the participant arrives to the VR lab they will be given a set of instructions regarding the experiment. First, a training session will take place followed by the two experiments of Virtual Reality. For each experiment, questionnaires will be used and at the end an additional one regarding participant's background information must be filled out.

Risks

A set of precautions were taken to avoid psychological and physical injury during the experiments. You may experience dizziness or nausea during the experiments. If you sense any of these tell the researcher to stop the experiment immediately if you think it is necessary. One of the researchers will help you sitting down and will provide a glass of water. It can also help to close your eyes while you sit down to counteract nausea. It is also important that you know that a first aid kit is available during the experiments.

I have accurately read out the informed consent and agree to participate on the experiments. The data obtained during my participation may be used for the purposes mentioned above.

Signature of Participant giving the consent:

____

Name ___________________________

Date ___________________________

DD/MM/YYYY

Appendix E: VR Unity project (Digital information)

Both, the Unity project and the applications developed for the experiment, were directly submitted to the Division of Fire Safety Engineering through the promoter of this project Enrico Ronchi.