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Abstract. A virtual reality (VR) experiment with 96 participants was carried out in a Cave Automatic Virtual Environment (CAVE) laboratory at Lund University to provide recommendations on the design of flashing lights at emergency exit portals for road tunnel emergency evacuation. A set of variables were investigated, namely 1) Colour of flashing lights, 2) Flashing rate, 3) The type of light source, 4) The number and layout of the lights on the portal (1 light on top of the exit door, 3 lights of which 1 on top and 2 on the sides of the exit door, or 2 bars on the sides of the exit door). An additional portal design variable has also been investigated, i.e. 5) The use of a window vs a painted running man on the exit door. Participants were immersed in a VR road tunnel emergency evacuation scenario and they were then asked to rank different portal designs using a questionnaire based on the Theory of Affordances. Results show that green or white flashing lights perform better than blue lights in the emergency exit portals. Flashing rate of 1 Hz and 4 Hz performed better than flashing rates of 0.25 Hz. A LED light source performed better than single and double strobe lights. Although the three layouts of the lights under consideration performed similarly, the use of a higher number of lights is deemed to be beneficial. If the door is visible, i.e., if no smoke is taken into consideration in the emergency scenario, the scenario with the running man painted on the door provides equal results compared to a door with a window. Nevertheless, the use of the window is recommended since it allows seeing behind the door, including the possibility to see the traffic in the opposite tunnel tube, and reduce people's hesitation.

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Disclaimer

Summary

This document is intended to assist road tunnel safety designers and operators in the assessment of the appropriate emergency systems in the case of road tunnel evacuation. In particular, the present work discusses and tests the characteristics of flashing lights at emergency exit portals using a Virtual Reality (VR) experiment. This report is part of the research project “Evacuation route design” (Utformning av utrymningsväg) funded by the Swedish Transport Administration (Trafikverket). Different systems for road tunnel evacuation emergencies are tested and evaluated within this research project. The results presented in this report will be used to assist the design of the evacuation systems in the Stockholm Bypass project.

Despite the fact that the use of flashing lights is recommended and some of their features have been investigated in isolation, there is the need to perform a systematic evaluation of the characteristics of flashing lights at emergency exit portals for road tunnel evacuation. The present work focuses on filling this gap by experimentally investigating some of the main characteristics concerning the design of flashing lights at tunnel emergency exit portals. In the present research, some of the aspects of the way-finding installations are fixed in order to match the design of the Stockholm bypass project. Apart from those fixed characteristics, variables that may potentially affect occupants’ decision to use emergency exits when using flashing lights have been reported to be (1) the colour of the light, (2) the flashing rate, (3) the type of light source, (4) the number and the layout of the lights. An additional variable of interest is (5) the use of a window on the exit door of the emergency exit portal in comparison with a painted running man on the door.

This work adopts Virtual Reality (VR) for the systematic study of the 5 variables presented above. A VR experiment was carried out in the VR laboratory at Lund University. Participants’ evaluation of the portal designs during the VR experiments is made using a questionnaire based on the Theory of Affordances.

Based on the VR experiment and the responses to the questions based on the Theory of Affordances, a set of recommendations can be provided: 1) Flashing lights should be present in the emergency exit portal design. 2) Recommended colours of flashing lights are either green or white; blue lights are not recommended. 3) The flashing rate should be between 1 Hz and 4 Hz. Flashing rates lower than 1 Hz are not recommended. Flashing rates higher than 4 Hz have not been investigated. 4) The type of light source should be LED (as defined in the present report), while single and double strobe lights are not recommended. 5) The layout and position of the lights can be either with 1 or 3 lights or 2 bars on the side of the door. Although the present experiment did not show significant differences between the cases with different lights, the use of more than one light is recommended since it can increase affordances (sensory, cognitive and functional) and further encourage evacuees in using the emergency exit. 6) The scenario with the running man painted on the door provided equal evaluation compared to the reference scenario (with a window on the door) if the door is visible in the experiment. Nevertheless, the use of the window is recommended since it allows seeing behind the door, including the possibility to see the traffic in the opposite tunnel tube, and reduce people’s hesitation.

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1.Introduction

Road tunnels are critical transportation infrastructures in terms of evacuation safety. The enclosed space may lead to the quick development of an untenable environment for the tunnel occupants, possibly leading to dangerous scenarios and serious consequences (Nilsson et al., 2009). This has been demonstrated by the fatalities caused by different accidents such as the Mont Blanc tunnel fire (Duffé and Marec, 1999) and the St Gotthard fire (Carvel and Beard, 2005). In this context, an optimal usage of tunnel emergency exit is crucial for the safety of occupants (Gandit et al., 2009; Ronchi, 2013).

Way-finding systems are a possible method to increase the level of safety of road tunnels by promoting appropriate route and exit choice, hence decreasing total evacuation time and exposure to risk (Ronchi et al., 2015). The effectiveness of way-finding systems is reflected in the likelihood that the occupants use an emergency exit (Heskestad, 1999; Ronchi et al., 2012b).

Different systems have been recommended to direct evacuating people for both smoke-filled environments (Boer and van Wijngaarden, 2004; Fridolf et al., 2013; Heskestad, 1999) and clear conditions (Nilsson et al., 2005; Tang et al., 2009). Among them, the use of flashing lights has been reported as a possible solution to encourage emergency exit usage (Nilsson, 2009). In fact, flashing lights in road tunnels can aid route choice and decrease uncertainty during exit choice (Cosma, 2014; Jin and Yamada, 1994; Nilsson, 2009). Despite the fact that the use of flashing lights is recommended and some of their features have been investigated in isolation (Cosma, 2014; Nilsson et al., 2005), there is the need to perform a systematic evaluation of the characteristics of flashing lights for road tunnel evacuation. In practical terms, the use of flashing lights is often recommended at road tunnel emergency exit portals, but only general information on their design is available (Nilsson, 2009).

The present study focuses on filling this gap by experimentally investigating some of the main characteristics concerning the design of flashing lights at tunnel emergency exit portals. The analysis of different studies and regulations (Allen et al., 1967; Crawford, 1963; De Lorenzo and Eilers, 1991; European Commission, 2004, p. 200; Gerathewohl, 1953; Nilsson et al., 2005; Vos and Van Meeteren, 1971) permitted the identification of the main variables concerning the design of flashing lights:

1) the colour of the light
2) the flashing rate
3) the type of light source
4) the number and the layout of the lights

An additional variable of interest has been identified as 5) the use of a window on the exit door of the emergency exit portal in comparison with a painted running man on the door.

This work adopts Virtual Reality (VR) for the systematic study of the 5 variables presented above (Kinateder et al., 2014c). In safety research (including tunnel safety research), VR has been successfully employed for different applications such as the study of the impact occupant training (Kinateder et al., 2013; Lin, 2002), social influence (Kinateder, 2013; Kinateder et al., 2014b), the influence of conflicting information on behaviour (Kinateder et al., 2014a), warning compliance (Duarte et al., 2014, 2010), way-finding (Kobes et al., 2010) and tunnel phobia (Mühlberger et al., 2007), etc.

In the present work, participants' evaluation of the portal designs during the VR experiments is made using a questionnaire based on the Theory of Affordances (Gibson, 1986; Hartson, 2003). The Theory of Affordances has been previously successfully employed in safety research to understand evacuation behaviour (Joo et al., 2013; Kim et al., 2011; Nilsson, 2009; Ronchi et al., 2014).

The present work has two main objectives. The first main objective is associated with the need to increase the understanding on the effectiveness of flashing lights by exploring the affordances they generate. For this reason, the objective is to present a method for the evaluation of tunnel safety installations. The second objective is to assist road tunnel safety engineers and operators in the design of the characteristics of flashing lights for road tunnel emergency exit portals. For this reason, the VR tunnel scenarios under consideration, as well as the design of flashing lights, have been selected in order to reflect current engineering practice. In fact, the results presented in this report will be used to assist the design of the evacuation systems in the Stockholm bypass project. In this manner, the results discussed in this work are intended to have a direct impact on tunnel safety design practice.

2. Methods

This section discusses the methods used to investigate the design of flashing lights at emergency exit portals in case of road tunnel evacuation. In the present study, a VR experiment (Kinateder et al., 2014c) has been used to evaluate the effectiveness of different setups of variables concerning the design of flashing lights at emergency exit portals. The Theory of Affordances (Gibson, 1986) is also briefly introduced since it has been used to design the Likert scale-type questionnaires administered to the participants of the experiment.

2.1. Virtual Reality

In order to study the characteristics of flashing lights at emergency exit portals, a Virtual Reality (VR) experiment was carried out at the VR laboratory at Lund University. VR can be defined as a "*real or simulated environment in which the perceiver experiences telepresence*", i.e., the feeling of being present in a virtual environment (Steuer, 1992). Despite this broad definition of VR, the term VR is used in the present work to refer to computer-generated environments. Telepresence is linked with the illusion of being immersed in the environment represented with the VR technology.

In present work, immersion in the VR environment has been achieved by carrying out experiments in a laboratory. The VR laboratory consists of a main hall (200 m^2 with a 7 m high ceiling) and a room for development and instruction to participants. The laboratory includes state of the art equipment in terms of Cave Automatic Virtual Environments (CAVE): the Black Box. This technology consists of a back projection system with three screen segments, each 4 m wide. In addition, the VR environment is also projected on the floor. The Black Box technology uses stereoscopy with polarized light. Participants navigate the virtual environment using a joypad and their position is monitored in real time with head ultrasound tracking. This creates a strong sense of presence and the user perceives the space approximately on a one to one scale (Wallergård et al., 2007).

VR is a relatively new approach in tunnel evacuation research. The great advantage associated with VR experiments is high experimental control (Kinateder et al., 2014c), which is in line with the scope of this work to systematically investigate different variables for similar conditions.

2.2. Theory of Affordances

A useful framework for the analysis of the design of evacuation systems, e.g., fire alarms, way-finding systems or simple emergency exits, is the Theory of Affordances (Gibson, 1986, 1977). According to Gibson's original theory, an object is perceived in relation to what it offers or affords the individual. An affordance is, hence, what the object offers the individual in relation to his or her goal. The discussion presented in this section on the use of the Theory of Affordances as a tool for questionnaire design is mostly based on Ronchi & Nilsson (2014).

The Theory of Affordances has been used in a variety of different research fields to analyse the design of everything from climbing routes (Boschker et al., 2002) to human-computer interaction design (Hartson, 2003). It has also been used to evaluate the design of emergency exits (Sixsmith et al., 1988) and to explain the effectiveness of way-finding systems for evacuation (Nilsson et al., 2009). In addition, the theory has been successfully employed in fire safety research to understand evacuation behaviour (Joo et al., 2013; Kim et al., 2011; Nilsson, 2009).

In order to enable the analysis of the affordances provided by an evacuation system, it is useful to divide affordances into different categories. One possible division has been proposed by Hartson (Hartson, 2003), who suggests that affordances be divided into the following four categories:

1) Sensory affordance: sensing or seeing
2) Cognitive affordance: understanding
3) Physical affordance: physically doing or using
4) Functional affordance: fulfilment an individual'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 the sensory, cognitive, physical and functional affordances provided by an evacuation system, it should be possible to identify conflicts and non-optimal design. Hence, the theory can be used to analyse an array of possible system designs in order to rule out the least appropriate system. However, this type of analysis requires ample understanding of the different types of affordances in relation to the examined system. The following sections therefore provide brief explanations of the four categories of affordances in relation to the types of systems that are studied in the present report, i.e., in relation to evacuation systems.

2.2.1. Sensory affordance

In order for an evacuation system to work as intended it must first be sensed, e.g., seen or heard, by the individual. This means that a design must provide sufficient sensory affordances to catch people's attention and be noticed. In addition, it must be possible to make out the details of the system, e.g., a written text message on an information sign should be legible and a voice alarm should be intelligible.

Previous research has shown that the contrast between the system and its surrounding influences sensory affordance. For example, if an emergency exit has the same colour or pattern as the walls it can easily be missed (Sixsmith et al., 1988). Similarly, a fire alarm with the same frequency as the background noise might not stick out, which suggests that a wide frequency range is appropriate to overcome a multitude of possible background noises (Palmgren and Åberg, 2010). Another way of increasing the attention capturing ability is to introduce an alternating pattern, e.g., flashing lights for visual systems (Nilsson, 2009) or pulsating sound for acoustic systems (Palmgren and Åberg, 2010). However, this still requires that the background does not alternate according to a similar pattern, and it is hence another way of providing contrast.

If an evacuation system is meant to convey complex information, it is particularly important that the details of the system can be easily discerned. For instance, it must be possible to make out the details of a pre-recorded evacuation message, which has been shown to be quite difficult in road tunnels due to the challenging acoustic environment (Nilsson et al., 2009).

2.2.2. Cognitive affordance

Cognitive affordances support the understanding of the observed evacuation system. This understanding is essential for the performance because inappropriate interpretations can lead to confusion and non-optimal behaviour. It is therefore essential to ensure that evacuation systems are properly understood, which can be achieved by consistent and well-considered designs.

In order to achieve appropriate cognitive affordances, i.e., to ensure that an evacuation system is interpreted as intended, it is useful to build on people's previous experiences and preferences. For example, the colour green can be used to signal *safety* or *go*, as these are the typical associations with green (Wickens, 2013). The colour red, on the other hand, can be used to keep people away because red is often associated with *danger* or *stop* (Wickens, 2013).

The cognitive affordances provided by a specific design can also be influenced by the context, i.e., the nature of the situation. This is exemplified by the misinterpretation of the traffic information signs during the fire in the Södra Länken tunnel in Stockholm on June 16, 2008 (Åberg et al., 2008). The written message on the signs was to *"evacuate tunnel"*, which lead many motorist to drive out through the dense smoke instead of leaving their vehicle and evacuating on foot. This example shows that, from the perspective of the motorist sitting in their vehicle, the message was interpreted differently than the designers had intended. It is therefore important to consider the context of the situation and to provide clear information that is not easily misinterpreted.

2.2.3. Physical affordance

Physical affordance supports the user physically doing something, such as opening a door. This type of affordance is therefore mainly applicable for evacuation systems that are physically used during evacuation. Examples include opening devices for doors or buttons for initiating two-way communication. In order for these types of systems to work, it is imperative that people can easily use them and the design should ideally support this use by being simple to operate. For example, a door handle should be easy to operate and a door should not be difficult to push open, e.g., should not require a large opening force.

Emergency exit portals are physically used during evacuation in road tunnels, which means that physical affordances are in general relevant for tunnel evacuations. For example, the design of the handle and the door leaf can potentially influence how difficult the door is to open. However, in the present study, only flashing lights at emergency exit portals are investigated, which means that mainly sensory, cognitive and functional affordances are relevant. Therefore, physical affordances are not discussed to a great extent in the present report.

2.2.4. Functional affordance

Functional affordance helps the user to achieve the desired goal and can be seen as the final outcome of the combination of sensory, cognitive and physical affordances. For road tunnels, the main goals should preferably be to reach a safe place, which requires people to overcome possible property attachment (Ronchi et al., 2012a; Shields, 2005), i.e., not be reluctant to leave their vehicle, and normative social influence (Nilsson and Johansson, 2009). In order to achieve appropriate functional affordance, this goal needs to the reinforced by the evacuation system. For example, an emergency exit portal that is easy to notice (sensory) and having a purpose that is easy to understand (cognitive) will also provide appropriate functional affordance. For systems that are physically used, e.g., emergency exit doors/portals, it is also relevant to include physical affordance when estimating the functional affordance.

2.2.5. Conflicting affordances

If an evacuation system is designed inappropriately, it can provide affordances that are in conflict with each other. For example, a system consisting of a green emergency exit sign with flashing orange lights may provide cognitive affordances that are in conflict (Nilsson, 2009). The sign might signal that the exits should be used for emergency evacuation, but the orange light might be interpreted as a warning. Conflicts may also arise between different types of affordances, e.g., sensory and cognitive.

The concept of conflicting affordances is considered very useful for understanding why certain evacuation systems are inappropriate. By systematically examining the sensory, cognitive, physical and functional affordances provided by a specific design, it is often possible to identify potential conflicts at an early stage of the design process.

3. The VR experiment on flashing lights

The VR environment consisted of a portion of a road tunnel based on the design of a real world project, i.e., the Stockholm bypass project (Modig et al., 2014). This section presents the list of installation setups under consideration, the experimental procedure and the results of the VR experiment.

3.1. Installation setups

Prior to running the experiments, pilot testing was performed in order to test the experimental procedure and scenarios. The selection of the specific installation setups under investigation was based on the most common designs of flashing lights for evacuation emergencies in engineering practice as well as the literature available on flashing lights designs (Allen et al., 1967; Crawford, 1963; De Lorenzo and Eilers, 1991; European Commission, 2004; Gerathewohl, 1953; Nilsson et al., 2005; Vos and Van Meeteren, 1971).

Table 1 presents a summary of the variables under consideration during the experiment and the corresponding installation setups.

Table 1. List of installation setups.

Variable	Installation setups
Colour	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 (see Figure 1)	2 Bars
	3 lights (2 on the sides and 1 on top)
	1 light
Door design (see Figure 2)	Painted running man
	window

Colours under consideration are green, white and blue. The most used colour for conveying safety messages in Europe is green, while white is generally used to convey information (International Standards Organization, 2011). Blue has also been included since a previous study found that it may be particularly effective for emergency signalling (McClintock et al., 2001, 2000). Previous research demonstrates that a flashing rate equal to 1 Hz performs well to encourage emergency exit usage (Nilsson et al., 2005). To systematically investigate different flashing rates, a factor of 4 was applied to this flashing rate to obtain a faster (4 Hz) and a slower (0.25 Hz) flashing rate. The light sources under investigation have been chosen in order to include the main commercial types available on the market (strobe, Light-Emitting Diode or LED and double strobe). Strobe and double strobe lights are currently employed in road tunnel emergency lighting systems, and they are installed generating a sudden electrical discharge. The characteristics of Light-Emitting Diodes (LED) are electrical efficiency and a longer lifespan if compared with incandescent lamps. They also present the advantage of a programmable length of the flashing, so for this reason they are often considered as the future technology for tunnel emergency lighting.

The layouts of the lights have been selected in order to reflect current engineering practice (such as in the real-world tunnel project associated with the present research study) in which the maximum number of lights can be affected by economic factors (i.e. no more than 3 lights are generally installed). Figure 1 refers to a schematic representation of the layout of the lights in the portal. Two different installation setups are taken into consideration in order to investigate the VR scenarios on door design, i.e. the scenario with a window on the door or the running man (see Figure 2).

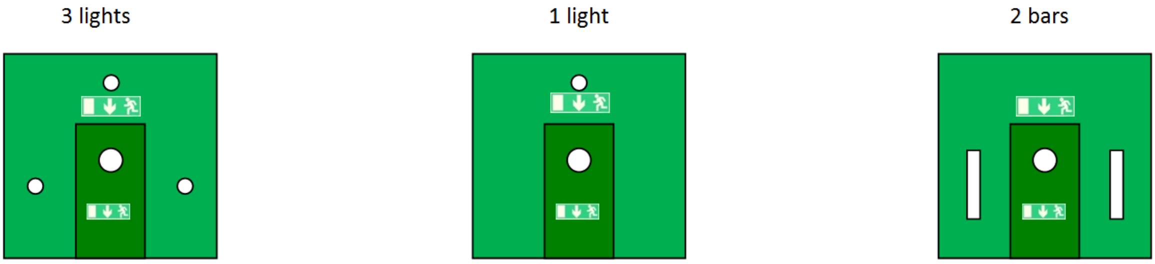

Figure 1. Schematic representation of the layout of the lights.

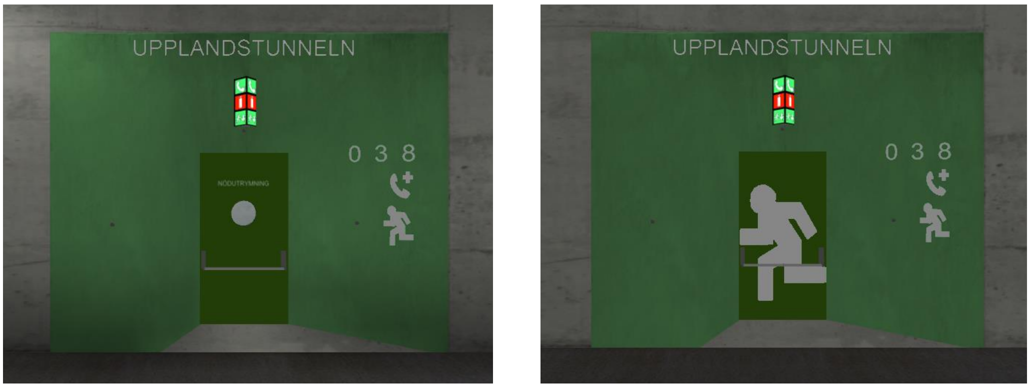

Figure 2. Exemplary representation of the VR emergency exit portal in presence of a window (left) or a running man (right) on the door.

3.2. The experiment

The VR evacuation experiment was carried out in Lund in May and June 2014 in the CAVE system situated in the Virtual Reality laboratory at Lund University. Approximately one month before the experiments, the recruitment started via advertisements at Lund University, emails, forums, websites, and social networks (see Appendix 1 for an example of recruitment letter).

Only brief information about the experiment was given. Participants voluntarily signed up for the experiment leaving their contact information. One day before the experiment, participants were contacted and reminded of the date and location of the experiments.

The VR environment consisted of a portion of a road tunnel based on the design of a real world project, i.e., the Stockholm bypass project (Modig et al., 2014) and it was drawn using a 3D modelling software (SketchUp™), and imported into the game engine Unity3D™. Tunnel occupants were requested to navigate the VR environment with the goal of reaching a safe place (i.e., an emergency exit) and rank different portal designs by responding to a Likert-scale type questionnaire based on the Theory of Affordances. During the experiments, the emergency exit portals were equipped with a number of different flashing lights. The rest of the environment has been constructed in VR in order to reproduce the actual design of the emergency systems available in the Stockholm bypass project, e.g. exit signage, traffic information signs, etc.

The variables and installation setups under consideration correspond to the configurations presented in Table 1. Strobe and LED lights have been reproduced in the VR environment after a careful evaluation of appropriate frame-rates. Given the streaming frame-rate adopted in the VR environment (approximately 65 frames per seconds by default), the pulse of the lights has been adjusted in order to be visible to human eye and be as similar as possible to the lights in the real world. After a set of iterative attempts in the CAVE system, the final pulses of the lights have been identified. A single strobe light was reproduced in VR with a pulse of 4 centi-seconds. The time interval between two double strobe lights was equal to 12 centi-seconds. The LED lights had duration equal to 50 centi-seconds. This flashing pattern for LED lights has been chosen since it has been shown in previous experiments to perform well (Nilsson et al., 2005). The intervals between different pulses were then modified to match the flashing rates. For instance, Figure 3 shows the case of flashing rate equal to 1 Hz.

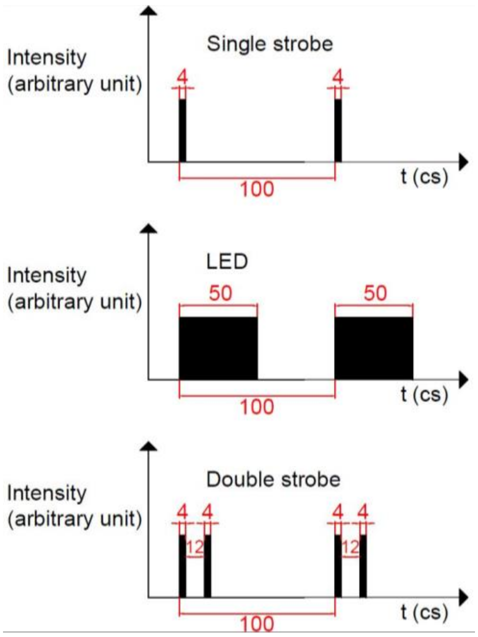

Figure 3. Schematic representation of the type (i.e., light pattern) of the light source. The x axis represents the time. All measures are expressed in centi-seconds.

3.2.1. Participants

A total of ninety-six (96) participants took part in the experiment (68 male and 28 female). Test participants' age ranged from 19 to 64 years old (average=25.15 years and standard deviation=7.4 years). Eighty-seven participants (90.6%) were of Swedish nationality, five participants were Danish (5.2%), two participants (2.1%) had double citizenship (Swedish and another citizenship) and 2 participants (2.1%) were not Swedish/Danish. Most of the participants (90 out of 96, i.e., 93.8 %) lived in Sweden, and all participants were Swedish speakers. The sample was mainly made of students (81 people, i.e., 84.4% of the participants), while the rest of the sample included people of different ages and professions (e.g. university employees, lecturers, technicians, managers, etc.). Participants did not declare to have sight impairments with the exception of four participants who declared to have difficulties in distinguishing red and green. Most of the participants (97.9 %) did not have previous experiences concerning tunnel evacuations.

Two participants (2.1%) declared previous experiences on tunnel evacuation such as the case of one participant experiencing the traffic being stopped while inside the car in a tunnel due to an accident and one participant with a previous experience on tunnel evacuation drills. Most of the participants (85 out of 96 participants, i.e., 88.5%) had a driving license. The largest part of the participants were not very frequent tunnel users, with the most common use being once per year (50.0%), followed by less than once per year (25.0%) and once per month (21.9%).

In general, the sample included participants with good videogame experience, with the largest share of participants declaring very big experience with videogames (32.3%), followed by big experience (28.1 %), little (17.7%), medium (12,5%) and very little (9.4%). The majority of the participants declare to have no previous experience on Virtual Reality experiments (96.9%). The participants were reimbursed with 200 SEK for their participation.

3.2.2. Experimental procedure

Participants took part at the experiment one at a time. Upon the arrival, each participant was guided to a zone of the lab (VR lab zone) separated from the CAVE lab. Here he/she was welcomed by a researcher and provided with written general information about the experiment, including safety measures and an informed consent form.

The participant was then guided to the CAVE system. During the experiments, one researcher was located in the proximity of the CAVE to ask the questions to the participant and another researcher was sitting at the computers in order to start/stop the scenarios and provide additional help during the experiments. Participants always had the right to abort the experiment at any time by contacting the researcher. When the participants arrived in the CAVE, they were requested by a researcher to wear the head tracking device and the 3D glasses, to remove their shoes, and to take the VR joypad in their hands. Participants were then briefly instructed on the equipment in use for the experiment, i.e. how to navigate the VR environment with the joypad. In order to get the participants familiar with the navigation system, they were asked to navigate through a training scenario. The scenario consisted of a labyrinth in which participants were required to find the exit through different corridors and doors. After the end of the training scenario, the experiment started.

Prior to running the experiments, the following information was read to the participants:

"*I försöket kommer du att uppleva och förflytta dig i en virtuell tunnelmiljö. Din uppgift är att förflytta dig till en säker plats. Du kommer att stå stilla i kuben (peka på kuben) och förflytta dig i den virtuella miljön med hjälp av en handkontroll. Du kommer därefter att titta på några olika tunnelutformningar samtidigt som du svarar på frågor. Var uppmärksam eftersom utformningarna skiljer sig lite från varandra."* [In the trial, you will experience and move through a virtual tunnel environment. Your task is to move to a safe location. You will stand still in the cube (point to the cave) and navigate in the virtual environment with a gamepad. You will then look at some different tunnel designs as you answer questions. Pay attention since the designs differs slightly from each other.]

"Deltagande i försöket är frivilligt. Du kan när som helst avbryta. Ge en signal till mig (försöksledaren) så stänger jag av VR-utrustningen. Du kommer att får din ersättning även om avbryter." [Participation in the study is voluntary. You can terminate the trial at any time. Give a signal to me (researcher) so I turn the VR equipment off. You will receive your compensation even if you interrupt the trial.]

"Det finns risk att du blir åksjuk eller yr i försöket. Du ska säga till mig (försöksledaren) om du börjar känna dig åksjuk eller yr. Jag hjälper dig att sätta dig ner och ger dig vatten att dricka. Det kan också hjälpa att blunda när du satt dig ner för att motverka illamående." [There is a risk that you get motion sickness or dizziness in the experiment. Please, tell me (experimenter) if you start to feel nausea or dizziness. I will help you to sit down and give you water to drink. It can also help to close your eyes when you sit down to counteract nausea.]

The researcher asked the test participants if the information was clear and the tunnel experimental scenario was initialized. The experiments were divided into two parts. Each participant took part in both of them. During the first part of the experiment, participants navigated a VR tunnel in the CAVE system (see Figure 4) and they were asked to find their way out to safety, e.g. to find an emergency exit. Their behaviour in the VR environment was observed by two researchers. The aim of this part was to make participant feel immersed in the tunnel emergency scenario. The emergency exit portals were equipped with four different reference configurations of installations. Alternative characteristics of the emergency exit portal were tested during the second part of the experiments. Participants were placed in front of the portal and asked to rank them through a Likert-scale type questionnaire based on the Theory of Affordances.

Figure 4. Test participant navigating into the reference tunnel evacuation scenario in the CAVE system.

Experimental testing was hence conducted in two parts:

<u>Experiment part 1</u>: A set of reference VR tunnel navigation scenarios

<u>Experiment part 2</u>: A set of scenarios about the ranking of different emergency exit portal designs

The flow chart in Figure 5 presents a schematic representation of the phases of the experiments.

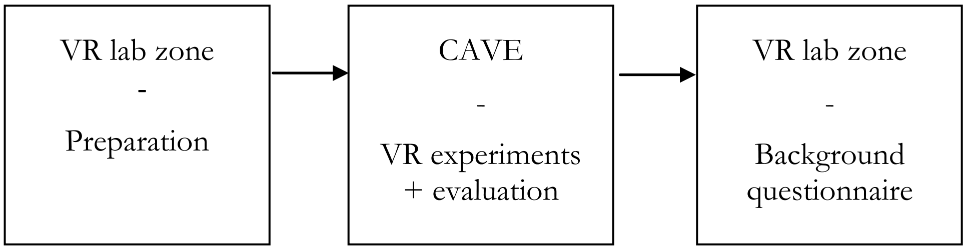

Figure 5. Flow chart of the phases of the experiment for each participant.

The total time employed to perform a complete test for each participant was approximately half an hour, which included preparation, navigation in the VR tunnel, evaluation of different designs and the completion of the background questionnaire. After completion, participants were then thanked for their participation and they were given basic information about the research project.

<u>Experiment Part 1</u>
In this part of the experiment, test participants were asked to find his/her way out to safety in a reference evacuation scenario. A fire alarm based on British Standards (British Standards, 2013) went off in the CAVE while test participants were initially located in the proximity of their car (outside the car) and their position was in the middle of two exits (Exit 1 and Exit 2 in Figure 6). The distance between the exits was defined in accordance with the Stockholm bypass project, i.e., 100 m. The virtual reality scenario had a total length of 200 m, where 100 m was the distance between the exits, which were distant 50 m from the ends of the VR scenario. The total length of the environment was longer and it included two curves at both ends of the scenario (see Figure 7).

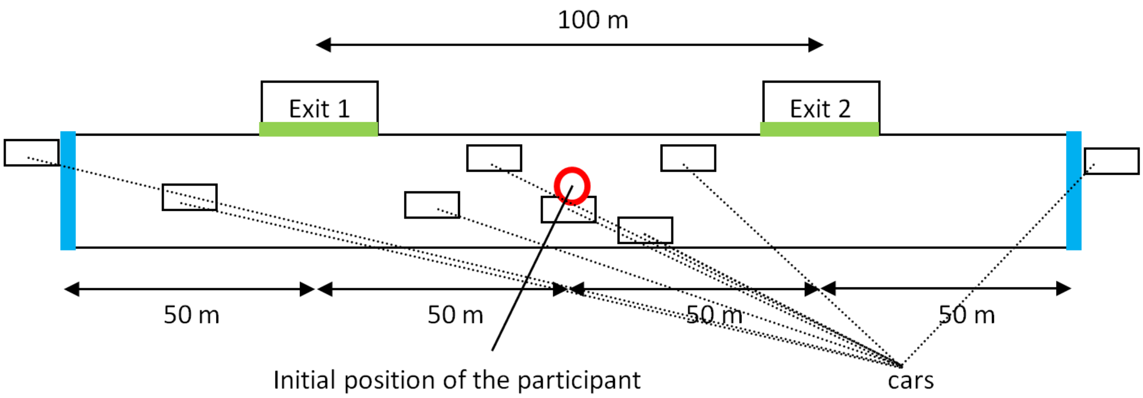

Figure 6. Schematic representation of the layout of the tunnel during the experiments. The elements within the tunnel (cars, exits, etc.) are off scale to facilitate the reading of the figure.

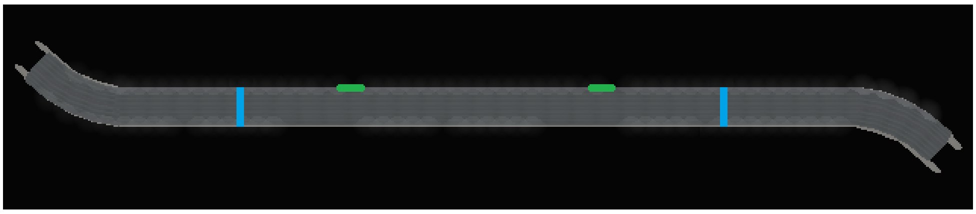

Figure 7. Schematic representation of the full VR environment. Green lines indicates emergency exits (off-scale to facilitate the reading of the figure) and blue lines indicates the end of the scenarios.

The scenario was automatically terminated if one of five possible conditions occur, i.e., if a participant reached one of the four targets or if he/she did not find any of them after a pre-defined time. The four targets were the two emergency exits (see green lines in Figure 6) and the areas that were more than 50 m past the exits in one of the two sides (see blue lines in Figure 6). The last condition was the case of a participant not reaching any target within 5 minutes (the scenario automatically terminates when the time expired).

<u>Experiment Part 2</u>

After the reference evacuation scenario was completed, the second part of the experiment started. Each participant was placed in a fixed position in the VR environment in front of different emergency exit portal designs (one at the time) for the analysis of different variables. Participants were in this case in front of an emergency exit portal design with a distance and angle of view, which permits the perception of the full portal in the VR environment (see Figure 8).

Figure 8. Example of the emergency exit portal view in the VR environment.

Participants were asked a set of questions by the researcher in the CAVE. Each participant was asked to rank a total of 7 portal configurations. Participants were asked to rank the designs answering 3 questions per configuration using a Likert scale (from -3 to +3). Questions were based on the theory of the affordance (Sensory, Cognitive and Functional Affordances).

The questions are presented here:

"*Du står nu framför en nödutgång i en vägtunnel. Besvara följande frågor om den aktuella utformningen. Du kommer att använda en 7-gradig skala där -3 är sämst och +3 är bäst. Till exempel kan en skala vara -3- extremt svårt, -2 – mycket svårt, -1 – svårt, 0 varken svårt eller lätt, +1 – lätt, +2 – mycket lätt, +3 - extremt lätt. Försök att sätta dig in i det scenariot du precis upplevt, dvs en utrymning i en vägtunnel, när du svarar på frågorna.*" [You are now standing in front of an evacuation portal in a road tunnel. Answer the following questions about the current design. You will use a 7-point scale where -3 is the worst and +3 is the best. For example, a scale can be -3 extremely difficult, -2 - very difficult, -1 - difficult, 0 is neither difficult nor easy, +1 - easy, +2 - very easy, +3 - extremely easy. Try to imagine the scenario that you just experienced, i.e., an evacuation in a road tunnel, when you answer the questions]

Question 1: *Ange på en skala från -3 till +3 hur lätt utformningen är att upptäcka.* [State on a scale from -3 to +3 how easy the design is to discover]

På skalan är -3 – extremt svårt och +3 - extremt lätt. [In the scale -3 is extremely difficult, and +3 is extremely easy]

Question 2: *Ange på en skala från -3 till +3 hur lätt det är att förstå att utformningen är en utgång som du ska använda*. [State on a scale from -3 to +3 how easy it is to understand that the design is an exit that you should use]

På skalan är -3 – extremt svårt och +3 - extremt lätt. [In the scale -3 is extremely difficult, and +3 is extremely easy]

Question 3: *Ange på en skala från -3 till +3 hur bra stöd utformningen erbjuder för din utrymning.* [State on a scale from -3 to +3 how good support the design offers for your evacuation]

På skalan är -3 – extremt dåligt och +3 - extremt bra." [In the scale -3 is extremely bad, and +3 is extremely good]

The option for an open comment about the experiments was also given to the participants at the end of the experiment. Each participant was therefore required to answer to 21 questions (3 questions per configuration). The answers of the participants were annotated in a spreadsheet by the researcher sitting at the computer desk of the VR lab.

3.2.3. Scenarios

The reference scenarios of experiment part 1 had four different configurations of the emergency exit portal in accordance with Table 2.

Table 2. Configuration of the emergency exit portal.

Scenario name*	**Colour**	**Flashing Rate**	**Type of light source**	**Layout and position**	**Number of participants**
RSfull	Green	1 Hz	LED	3 lights	24
FR1full	Green	2 Hz	LED	3 lights	24
TL1full	Green	1 Hz	Strobe	3 lights	24
LP1full	Green	1 Hz	LED	2 Bars	24

**Legend: RS=Reference Scenario, FR=Flashing rate, TL= Type of lights, LP= Light position*

In experiment part 2, four variables (plus an extra scenario investigating the design of the door) were investigated, each one including 3 possible configurations of emergency exit portals (See Table 3). One configuration (RS in bold in Table 3) was available in each variable (green colour, frequency of light equal to 1 Hz, LED light source and 3 lights). Two additional configurations were also included in experiment part 2 in order to control questionnaire fatigue (one configuration was repeated both at the beginning and at the end of the test) and test the effectiveness of the Likert scale (one configuration with no lights at all on the portal was included in order to verify if low scores were observed in the Likert scale).

Table 3. Scenarios of the experiment part 2. Installation setups are presented in relation to the variables under investigation. The combinations in bold represent the scenarios that present the same configuration.

Scenario name*	Variable under investigation	Colour	Flashing Rate	Type of light source	Layout and position
RS	Colour	**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= colour (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*

Each participant was placed in front of seven configurations (plus the initial tunnel navigation in experiment part 1, see also Table 4). The reference scenario RS and the scenario with no lights (NO) were administered to all 96 participants. All other scenarios (C1, C2, FR1, FR2, TL1, TL2, LP1, LP2, E and the repeated question) were administered to 48 participants. The configurations were presented in 8 different randomized orders (see Table 4) to avoid systematic errors due to the order of the questions.

Table 4. Randomization of the different configurations administered to test participants.

order 1	RSfull	RS	C1	C2	NO	E	FR1	FR2
order 2	RSfull	RS	C2	C1	NO	FR2	FR1	RS
order 3	FR1full	FR1	RS	FR2	NO	C1	C2	E
order 4	FR1full	FR1	FR2	RS	NO	C2	C1	FR1
order 5	TL1full	TL1	RS	TL2	NO	LP1	LP2	E
order 6	TL2full	TL1	TL2	RS	NO	LP2	LP1	TL1
order 7	LP1full	LP1	RS	LP2	NO	E	TL1	TL2
order 8	LP1full	LP1	LP2	RS	NO	TL2	TL1	LP1

3.2.4. Results

In order to control questionnaire fatigue, the first set of questions relating to the first scenario administered to the test participants was repeated. This is because there is one set of questions (first and last) that is repeated in 48 cases (half of the total sample that is 96, see order 2, 4, 6, and 8 in Table 4). The reason is to evaluate if there is a trend of questionnaire fatigue in the responses and if test participants are consistent in their answers. The analysis of the repeated answers to the same installation setup (i.e. testing of questionnaire fatigue) has been performed using a Wilcoxon signed-rank test and excluding the top scores. This analysis showed no significant impact of questionnaire fatigue on results ($p>0.05$). Thus the first answers to the repeated questions have been used in the analysis.

Descriptive statistics of the Likert-scale responses to the questions about sensory (Question 1), cognitive (Question 2) and functional affordance (Question 3) are shown in Table 5 and Figure 9, Table 6 and Figure 10, and Table 7 and Figure 11 respectively.

Table 5. Descriptive statistics of the Likert scale responses to the question 1 on sensory affordance (-3 is the minimum score, while +3 is the maximum score). The code ":1" is used to refer to question 1.

Scenario	**Description**	**N**	**Mean**	**Σ (St. dev.)**	**Min**	**Max**	**Percentiles**		
							25th	**50th (Median)**	**75th**
RS:1	Reference	96	2.74	.441	2	3	2	3	3
C1:1	White lights	48	2.42	.710	1	3	2	3	3
C2:1	Blue lights	48	1.21	1.071	-1	3	0	1	2
FR1:1	Fast flashing	48	2.77	.425	2	3	3	3	3
FR2:1	Slow flashing	48	1.79	.898	0	3	1	2	2
TL1:1	Single Strobe	48	1.94	.755	0	3	2	2	2
TL2:1	Double Strobe	48	2.23	.627	1	3	2	2	3
LP1:1	2 bars	48	2.71	.504	1	3	2	3	3
LP2:1	1 light	48	2.38	.672	1	3	2	2	3
NO:1	No lights	96	.31	1.225	-3	3	-1	1	1
E:2	Running man	48	2.73	.536	1	3	3	3	3

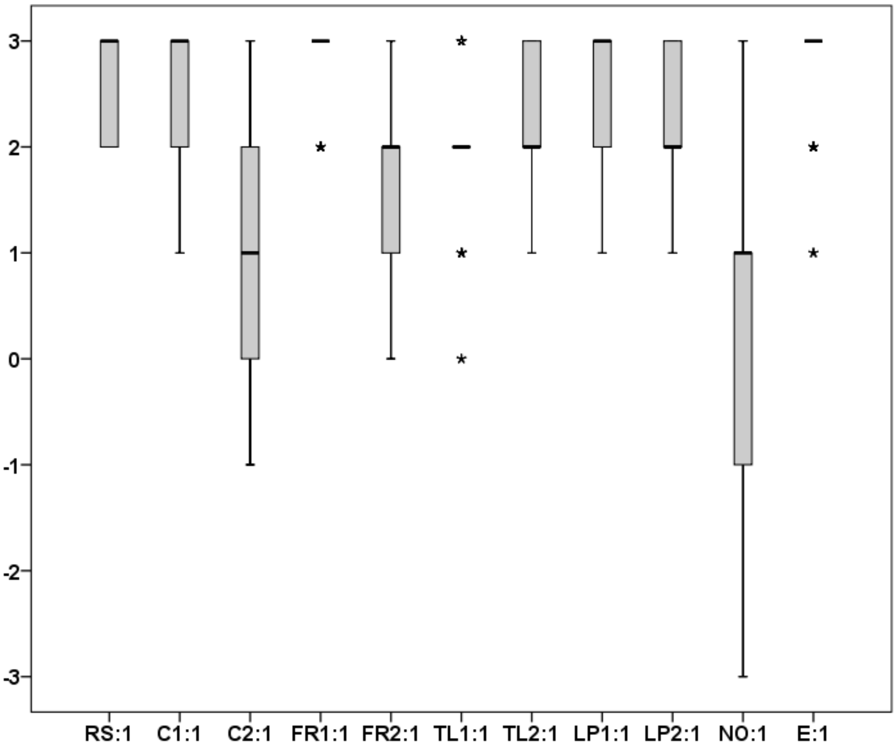

Figure 9. Boxplots of the Likert scale responses to the question on sensory affordance. The x-axis refers to the scenario under consideration, while the y-axis refers to the scores (where -3 is the minimum score, while +3 is the maximum score).

Table 6. Descriptive statistics of the Likert scale responses to the question 2 on cognitive affordance (-3 is the minimum score, while +3 is the maximum score). The code ":2" is used to refer to question 2.

Scenario	Description	N	Mean	σ (St. dev.)	Min	Max	Percentiles		
							25th	50th (Median)	75th
RS:2	Reference	96	2.49	.665	0	3	2	3	3
C1:2	White lights	48	2.21	.988	-1	3	2	2	3
C2:2	Blue lights	48	1.48	1.203	-1	3	1	2	3
FR1:2	Fast flashing	48	2.56	.741	0	3	2	3	3
FR2:2	Slow flashing	48	2.08	1.108	-1	3	1	3	3
TL1:2	Single Strobe	48	2.10	.778	1	3	1	2	3
TL2:2	Double Strobe	48	2.12	.789	-1	3	2	2	3
LP1:2	2 bars	48	2.56	.542	1	3	2	3	3
LP2:2	1 light	48	2.29	.651	1	3	2	2	3
NO:2	No lights	96	1.15	1.361	-3	3	0	1	2
E:2	Running man	48	2.83	.429	1	3	3	3	3

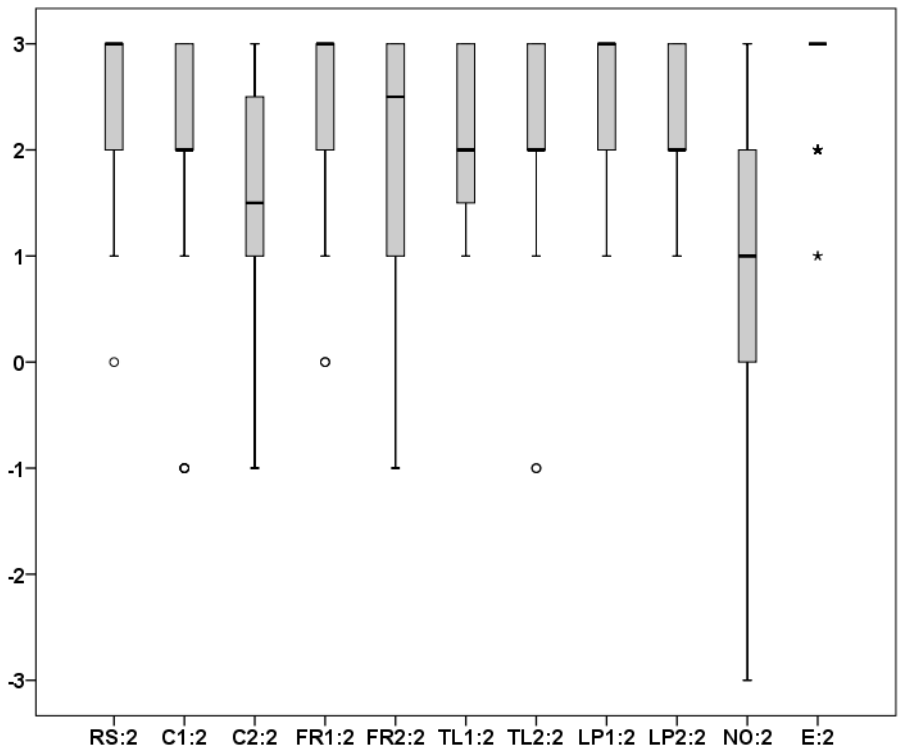

Figure 10. Boxplots of the Likert scale responses to the question on cognitive affordance. The x-axis refers to the scenario under consideration, while the y-axis refers to the scores (where -3 is the minimum score, while +3 is the maximum score).

Table 7. Descriptive statistics of the Likert scale responses to the question 3 on functional affordance (-3 is the minimum score, while +3 is the maximum score). The code ":3" is used to refer to question 3.

Scenario	Description	N	Mean	σ (St. dev.)	Min	Max	Percentiles		
							25th	50th (Median)	75th
RS:3	Reference	96	2.42	.627	0	3	2	2	3
C1:3	White lights	48	2.31	.748	0	3	2	2	3
C2:3	Blue lights	48	1.38	1.123	-1	3	1	1	2
FR1:3	Fast flashing	48	2.40	.818	0	3	2	3	3
FR2:3	Slow flashing	48	1.79	.898	0	3	1	2	2
TL1:3	Single Strobe	48	1.90	.831	0	3	1	2	2
TL2:3	Double Strobe	48	2.04	.617	1	3	2	2	2
LP1:3	2 bars	48	2.56	.580	1	3	2	3	3
LP2:3	1 light	48	2.23	.627	1	3	2	2	3
NO:3	No lights	96	.66	1.255	-3	3	0	1	1
E:3	Running man	48	2.65	.565	1	3	2	3	3

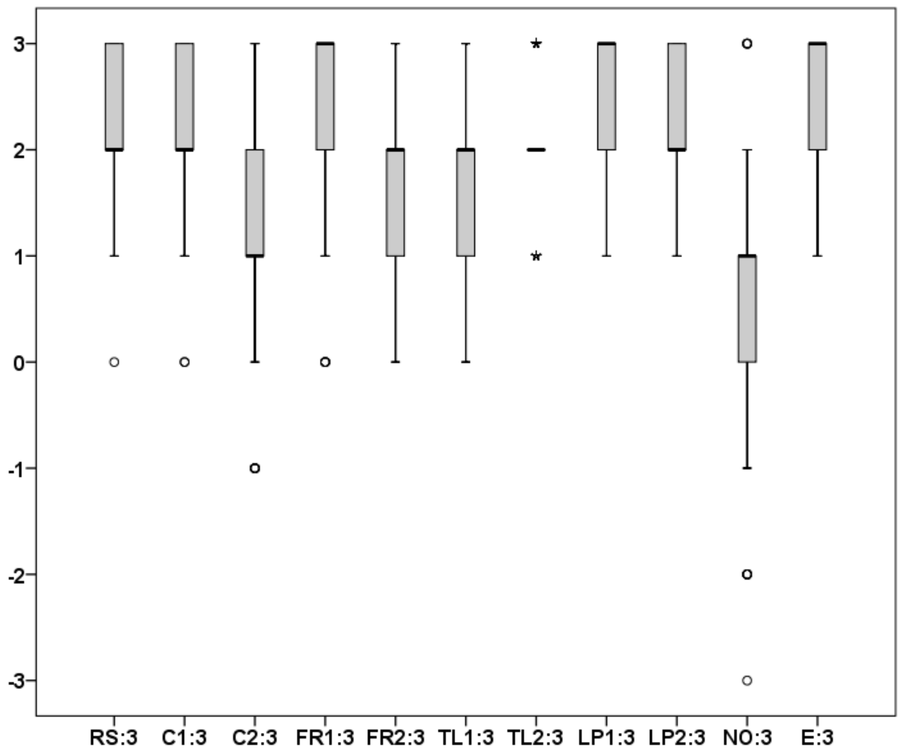

Figure 11. Boxplots of the Likert scale responses to the third questions on the overall evaluation of the designs (functional affordance). The x-axis refers to the scenario under consideration, while the y-axis refers to the scores. The boxplots are here ordered (from left to right) in relation to increasing scores.

Differences in the percentiles of scores for different designs can be observed among the responses of the test participants. Although the Likert scale results are treated here as ordinal values, the mean and standard deviations (which may be considered while studying the scores as a scale) seem to indicate a trend of differences among the scenarios. Therefore, inferential statistics are used to further investigate if the differences are statistically significant.

As a first step, in order to identify where the scores are statistically different in terms of sensory and cognitive affordance, two sets of Wilcoxon signed-rank tests are performed. The scenario RS is the reference scenario; the differences between the reference and the alternative designs is statistically evaluated for both sensory and cognitive affordance (see Table 8 and Table 9).

Table 8. Results of the Wilcoxon signed-rank tests for sensory affordance. The parts in grey indicate scenarios which resulted statistically different than the reference scenario.

	C1:1 - RS:1	**C2:1 - RS:1**	**FR1:1 - RS:1**	**FR2:1 - RS:1**	**TL1:1 - RS:1**
Z	-2.057[a]	-5.778[a]	-1.732[b]	-4.970[a]	-5.512[a]
Asymp. Sig. (2-tailed)	.040	.000	.083	.000	.000
	TL2:1 - RS:1	**LP1:1 - RS:1**	**LP2:1 - RS:1**	**NO:1 - RS:1**	**E:1 - RS:1**
Z	-4.746[a]	-1.500[a]	-3.989[a]	-8.457[a]	-.180[b]
Asymp. Sig. (2-tailed)	.000	.134	.000	.000	.857

a. Based on positive ranks
b. Based on negative ranks

Table 9. Results of the Wilcoxon signed-rank tests for cognitive affordance. The parts in grey indicate scenarios which resulted statistically different than the reference scenario.

	C1:2 - RS:2	C2:2 - RS:2	FR1:2 - RS:2	FR2:2 - RS:2	TL1:2 - RS:2
Z	-2.309[a]	-4.876[a]	-.421[b]	-3.311[a]	-2.678[a]
Asymp. Sig. (2-tailed)	.021	.000	.674	.001	.007
	TL2:2 - RS:2	**LP1:2 - RS:2**	**LP2:2 - RS:2**	**NO:2 - RS:2**	**E:2 - RS:2**
Z	-2.995[a]	-.991[b]	-1.886[a]	-6.894[a]	-3.989[b]
Asymp. Sig. (2-tailed)	.003	.322	.059	.000	.000

a. Based on positive ranks
b. Based on negative ranks

A Bonferroni corrections is applied on the results of the Wilcoxon signed-rank test (corrected significance level α_c=0.0083). Considering the corrected significance levels, the scenarios that appear statistically different from the reference scenario (which is preferred) in the study of sensory affordance are (see boxes in grey in Table 3): C2 (blue lights), FR2 (slow flashing), TL1 (single strobe), TL2 (double strobe), LP2 (one light) and NO (no lights). Similarly, for the case of cognitive affordance (see boxes in grey Table 4), the statistically significant scenarios are the same of the case of sensory affordance with the exception of the scenario LP2, which has been ranked equally to the RS in terms of cognitive affordance and the extra scenario E, which is ranked higher than the RS.

A qualitative evaluation of the descriptive statistics of the responses of the evacuees seems to indicate that functional affordance is positively correlated to sensory and cognitive affordance. For this reason, the following part discusses the comparison of different installation setups by analysing the scores assigned by test participants to the question on functional affordance. In fact, this last variable is used to perform an overall evaluation of the installation setups under consideration. The responses to the questions related to sensory and cognitive affordance will be used in the discussion section to identify which factors contribute to the effectiveness of different installation setups of flashing lights.

Also in the case of functional affordance, a set of Wilcoxon signed-rank tests is performed to compare different configurations with the reference scenario RS with regards to the responses to the question on functional affordance. The paired comparisons of all scenarios with the reference scenarios for question 3 on the overall evaluation of the scenarios (functional affordance) are presented in Table 10. Test statistics are presented in Table 11 (Table 11 shows in grey the cases in which significant differences are found).

Table 10. Paired comparisons of all scenarios with the reference scenario for question 3 on functional affordance.

Comparison		N	Mean Rank	Sum of Ranks
Reference vs white lights (RS:3 vs C1:3)	Negative Ranks	10	9.00	90.00
	Positive Ranks	7	9.00	63.00
	Ties	31		
	Total	48		
Reference vs blue lights (RS:3 vs C2:3)	Negative Ranks	32	17.19	550.00
	Positive Ranks	1	11.00	11.00
	Ties	15		
	Total	48		
Reference vs fast flashing (RS:3 vs FR1:3)	Negative Ranks	6	10.17	61.00
	Positive Ranks	10	7.50	75.00
	Ties	32		
	Total	48		
Reference vs slow flashing (RS:3 vs FR2:3)	Negative Ranks	23	12.61	290.00
	Positive Ranks	1	10.00	10.00
	Ties	24		
	Total	48		
Reference vs single strobe (RS:3 vs TL1:3)	Negative Ranks	24	14.31	343.50
	Positive Ranks	3	11.50	34.50
	Ties	21		
	Total	48		
Reference vs double strobe (RS:3 vs TL2:3)	Negative Ranks	21	12.05	253.00
	Positive Ranks	2	11.50	23.00
	Ties	25		
	Total	48		
Reference vs 2 bars (RS:3 vs LP1:3)	Negative Ranks	4	7.00	28.00
	Positive Ranks	9	7.00	63.00
	Ties	35		
	Total	48		
Reference vs 1 light (RS:3 vs LP2:3)	Negative Ranks	15	10.00	150.00
	Positive Ranks	4	10.00	40.00
	Ties	29		
	Total	48		
Reference vs no lights (RS:3 vs NO:3)	Negative Ranks	85	44.61	3792.00
	Positive Ranks	2	18.00	36.00
	Ties	9		
	Total	96		
Reference vs running man (RS:3 vs E:3)	Negative Ranks	4	7.50	30.00
	Positive Ranks	11	8.18	90.00
	Ties	33		
	Total	48		

Table 11. Results of the Wilcoxon tests for functional affordance. The parts in grey indicate scenarios which resulted statistically different than the reference scenario.

	C1:3 - RS:3	C2:3 - RS:3	FR1:3 - RS:3	FR2:3 - RS:3	TL1:3 - RS:3
Z	-.728[a]	-4.979[a]	-.393[b]	-4.258[a]	-3.976[a]
Asymp. Sig. (2-tailed)	.467	.000	.694	.000	.000
	TL2:3 - RS:3	**LP1:3 - RS:3**	**LP2:3 - RS:3**	**NO:3 - RS:3**	**E:3 - RS3**
Z	-3.922[a]	-1.387[b]	-2.524[a]	-8.061[a]	-1.886[b]
Asymp. Sig. (2-tailed)	.000	.166	.012	.000	.059

a. Based on positive ranks
b. Based on negative ranks

A Bonferroni correction is applied on the results of the Wilcoxon tests since multiple comparisons have been carried out (a within subject questionnaire). This means that the significance level, which is originally $\alpha=0.05$, should be divided by 6, i.e. corrected significance level $\alpha_c=0.0083$.

Considering the corrected significance levels, the scenarios that appear statistically different from the reference scenario RS are: C2 (blue lights), FR2 (slow flashing), TL1 (single strobe), TL2 (double strobe), NO (no lights). This means that the reference scenario is preferred over those scenarios (i.e. they have a higher proportion of lower scores than the reference scenario). Table 12 presents a summary of the results of all questions.

The other scenarios do not statistically differ from the reference scenario. These scenarios include the use of white lights (C1), faster flashing rate (FR1), two bars (LP1), and 1 light (LP2) and the extra scenario with the running man (E).

These conclusions are in line with the analysis of descriptive statistics (see Table 7), where the lowest scores are obtained for the cases of no lights (μ=0.66m), blue lights (μ=1.38m), slow flashing (μ=1.79), single strobe (μ=1.90), and double strobe (μ=2.04) m. The rest of scenarios presented a mean score μ always higher than 2.20.

Table 12. Summary of the results of the Wilcoxon tests for all affordances. The symbol "≠" refers to scenarios statistically different, while the symbol "=" refers to scenario statistically equal.

Scenario comparison	Scenario under consideration	Sensory	Cognitive	Functional
C1 - RS	White lights	=	=	=
C2 - RS	Blue lights	≠	≠	≠
FR1 - RS	Fast flashing	=	=	=
FR2 - RS	Slow flashing	≠	≠	≠
TL1 - RS	Single Strobe	≠	≠	≠
TL2 - RS	Double Strobe	≠	≠	≠
LP1 - RS	2 bars	=	=	=
LP2 - RS	1 light	≠	=	=
NO - RS	No lights	≠	≠	≠
E - RS	Running man on the door	=	=	=

4. Discussion

Based on the virtual reality experiment and the responses to the affordance-based questionnaire, this work represents a first attempt to provide detailed recommendations on the design of flashing lights at emergency exit portals in case of road tunnel evacuation.

The first evident trend is that flashing lights at emergency exit portals have a positive impact on emergency exit usage. In fact, the control scenario with no flashing lights received the lowest rank among all possible installation setup. This is in line with previous experimental work (Jin and Yamada, 1994; Nilsson, 2009; Nilsson et al., 2005).

The recommended colours of flashing lights are either green or white. In contrast with previous experimental research (McClintock et al., 2001, 2000), blue lights are not recommended since they were ranked with lower scores if compared with white or green.

The analysis of the flashing rates under consideration demonstrated that flashing rates in a range between 1-4 Hz seems to perform better than a rate equal to 0.25 Hz. Previous research shows that flashing rates in the order of 1 Hz perform well for encouraging emergency exit usage (Nilsson, 2009). The present study confirms this finding and demonstrates that a similar impact can be found for flashing rates in the range of 4 Hz. The low scores for the flashing rate equal to 0.25 Hz could be associated with the fact that a lower flashing rate may lead to a lower degree of perceived urgency, as well as have a lower capability of capturing the attention of the evacuees. In fact, the scores of scenario FR2 (0.25 Hz) were significantly lower than the reference scenario (1 Hz) for both sensory and cognitive affordance.

The study of the impact of different light sources on flashing lights effectiveness demonstrated that LED lights (in accordance to the schematic representation as presented for example in Figure 3) performed significantly better than single and double strobe lights. This finding can have a significant impact on the design of tunnel emergency installations and the cost effectiveness of the safety design since the choice of the light source may substantially affect the installation costs. In addition, it should be noted that LED technology can be programmable, thus designers should use it to produce effective lighting patterns.

The layout and position of the lights can be either with 1 or 3 lights or 2 bars on the side of the door, i.e., no significant differences have been found among different installation setups. This result seems to indicate that the layout of the lights doesn't seem to have any impact on people evaluation (scores are not statistically different). Nevertheless, the use of one light received significantly lower ranking than the reference scenario (including 3 lights) in terms of sensory affordance, but no statistical differences in terms of cognitive affordance.

With regards of the scenario with the running man painted on the door, equal scores were found for all affordances compared to the reference scenario (with a window on the door). Nevertheless, the window allows seeing behind the door, including the possibility to see the traffic in the opposite tunnel tube, and reduce people's hesitation. For this reason, the use of the window is recommended.

A discussion should be made on the impact of the sample under consideration in the present study, i.e., it was mostly made by Swedish students with driving license but limited tunnel evacuation experience. Some of the characteristics of the sample are in line with the characteristics of tunnel users found in a survey (Gandit et al., 2009). Given the scope of the study (the evaluation of different visual evacuation systems), the characteristics of the sample are deemed to allow a generalizability of results for able-bodied adults. No generalization of the results can be made for people with sight impairments (given the low number of people declaring issues with sights). Similarly, it should be noted that the present study has been carried out with a European sample, thus the use of these findings should consider the fact that colours may have different meanings in different cultures (Galea et al., 2010; Lai, 2010), i.e., the applicability of these findings should be carefully reviewed in light of the cultural context of application (for instance, emergency exit signs are generally written in red rather than green in the United States and this could affect the possible answers of test participants).

The use of Virtual Reality as a research method permitted the obtainment of a significant amount of data (576 individual observations have been collected including a total of 1728 measurements) with good cost-effectiveness and ecological validity. This is confirmed by the fact that most of the findings of this work are in line with previous experimental research conducted in real world environment (Jin and Yamada, 1994; Nilsson, 2009; Nilsson et al., 2005). This has been possible given the nature of the study. In fact, since the evacuation system under consideration consisted of a visual system, the VR environment represented a valid alternative to physical experiments. This would have been more difficult if the evacuation system was a physical system, i.e., ecological validity may have decreased for the case of a system that requires a physical action (such as the test of a handle for an emergency exit door, etc.). Virtual Reality permitted high experimental control and repeatability of the scenarios for different participants. The findings of this work give a positive contribute to the ongoing debate on the benefits of the use of Virtual Reality for fire evacuation research (Kinateder et al., 2014c). Future studies should further investigate and discuss the limitations and advantages of Virtual Reality in relation to other fields of applications (e.g. this work only investigates a visual system).

From a methodological perspective, another interesting finding of this work is that the use of the Theory of Affordances for questionnaire design permitted a detailed evaluation of evacuation systems. In fact, the study of sensory and cognitive affordances allowed a deep interpretation of the characteristics associated with the effectiveness of different installation setups. In this context, the validity of the results obtained using the Theory of Affordances in VR experiments is demonstrated by the agreement with previous experimental research (Jin and Yamada, 1994; Nilsson, 2009; Nilsson et al., 2005).

5. Recommendations on flashing lights and exit design

Based on the virtual reality experiment and the responses to the questions based on the Theory of Affordances, a set of recommendations can be provided in order to assist the design of portals in the Stockholm bypass project:

- Flashing lights should be present in the emergency exit portal design
- Recommended colour of flashing lights are either green or white; blue lights are not recommended
- The flashing rate should be between 1 Hz and 4 Hz. Flashing rates lower than 1 Hz are not recommended. Flashing rates higher than 4 Hz have not been investigated
- The type of light source should be LED (in accordance to the schematic representation presented in Figure 1), while single and double strobe lights are not recommended.
- The layout and position of the lights can be either with 1 or 3 lights or 2 bars on the side of the door. Although the present experiment did not show significant differences between the cases with different lights, the use of more than one light is recommended since it can increase affordances (sensory, cognitive and functional) and further encourage evacuees in using the emergency exit.
- The scenario with the running man painted on the door provided equal evaluation than the reference scenario (with a window on the door) if the door is visible in the experiment. Nevertheless, the experiment under consideration took into account only the case in which the doors are clearly visible (i.e. no smoke is taken into consideration in the emergency scenario). For this reason, it is in any case recommended to adopt the use of a window in the door since the window allows the evacuee to see behind the door, thus further enhancing the emergency exit usage, avoiding hesitation or permitting to see the traffic behind the door when moving to the adjacent tunnel tube.

6. Future research

This study gives a set of recommendations on the design of flashing lights at emergency exit portals in case of road tunnel evacuation. The study represents a systematic attempt to use Virtual Reality to test different configurations and enhance the safety conditions of road tunnels.

The present work demonstrates that VR is a methodology that can be successfully used for the study of evacuation systems. For this reason, future studies could use the same methodology to investigating affordances of different types of evacuation systems and design solutions (e.g. signage, location of the exits, etc.). This will allow a better understanding on the effectiveness of different evacuation systems as well as deepening the underlying relationships between affordances for any type of tunnel evacuation system. The final aim of the branch of research discussed in this work is therefore design optimization through Virtual Reality (allowing comparison and prioritization among different evacuation systems). The current study represents a significant methodological contribute for the assessment of optimal tunnel safety installations.

The present study investigates a significant range of installation setups and variables concerning the design of flashing lights at emergency exit portals. In fact, it is important to note that the present study aimed at considering the most important variables affecting the design of flashing lights at emergency exit portals. However, future studies could further expand the number of variables and setups under consideration. For instance, they could investigate different light configurations and/or types of lights, different colours or evacuation scenarios, a wider range of flashing rates, etc.

Another interesting future direction of VR for evacuation research is the study of human behaviour in low visibility conditions. Recent advances in VR allow not only the rendering of the smoke caused by a fire in a given condition, but also the study of a scenario in which there is a coupled integration of low visibility and human behaviour. The coupled fire-evacuation representation in VR and the impact of smoke on human behaviour still needs dedicated studies. In fact, also in this case, the Theory of Affordances could be used in future studies for the evaluation of human behaviour in low visibility conditions.

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Appendix 1. Example of recruitment letter

Rekryteringsinformation

LUNDS TEKNISKA HÖGSKOLA
Lunds universitet

Brandteknik och riskhantering
Daniel Nilsson

Utvärdering av utrymningssäkerhet i vägtunnlar

I slutet av våren 2014 kommer försök att genomföras i en virtuell vägtunnel i Virtual Reality-lab på IKDC. Syftet med försöken är att undersöka hur vägtunnlar bör utformas för att personer ska hitta till säkerhet i utrymningssituationer. Deltagarna får **200 kr efter skatt** (vid 30% skatteavdrag) i ersättning och dessutom ingår en kortare brandskyddsgenomgång.

Bakgrund och syfte

Tidigare olyckor i vägtunnlar har visat att bränder kan leda till stor skada. Ett exempel på detta är branden i vägtunneln Mont Blanc där 39 personer dog. För att undvika denna typ av olyckor i framtiden behövs mer kunskap om hur vägtunnlar ska utformas för att personer snabbt ska hitta till säkerhet.

Syftet med studien är att undersöka hur tunnlar bör utformas för att personer snabbt ska hitta till säkerhet. Målet är att ta fram en design som kan användas i framtida vägtunnlar.

Hur går studien till?

I försöket kommer du att uppleva och förflytta dig i en virtuell tunnelmiljö. Denna miljö visas i den så kallade *"kuben"*, vilken består av fyra skärmar (tre väggar och ett golv) som visar den virtuella miljön i tre dimensioner (3D). Du kommer att stå stilla i kuben och förflytta dig i den virtuella miljön med hjälp av en handkontroll. Du kommer därefter att titta på några olika utformningar samtidigt som du svarar på frågor. Försöket tar maximalt 30 minuter att genomföra.

Hur anmäler jag intresse?

Du anmäler ditt intresse genom att skriva upp dig på den lista som skickas runt på någon av informationsträffarna eller genom att gå in på följande länk och boka en tid:

http://doodle.com/ …..

Du bör inte delta i studien om du har epilepsi. När du anmält dig får du mer information om försöket via mejl eller sms.

Vem är ansvarig?

Försöken genomförs av forskare på avdelningen Brandteknik, LTH. Huvudansvarig forskare är Daniel Nilsson. Du kan nå Daniel via mejl (daniel.nilsson@brand.lth.se) eller telefon (046–222 95 93).