Interim Report: Flashing Lights for Road Tunnel Emergency Exit Portals - A Virtual Reality Experiment

Ronchi, Enrico; Nilsson, Daniel

2014

Interim Report: Flashing Lights for Road Tunnel Emergency Exit Portals - A Virtual Reality Experiment

Enrico Ronchi
Daniel Nilsson

Department of Fire Safety Engineering
Lund University, Sweden

Brandteknik och riskhantering
Lunds tekniska högskola
Lunds universitet

Report 7041. Lund 2014

Interim Report: The Use of Flashing Lights in Road Tunnel Emergency Exit Portals - A Virtual Reality Experiment

Enrico Ronchi
Daniel Nilsson

Lund 2014

Interim Report: The Use of Flashing Lights in Road Tunnel Emergency Exit Portals - A Virtual Reality Experiment

Enrico Ronchi and Daniel Nilsson

Report 7041

Number of pages: 15

Illustrations: Enrico Ronchi and Daniel Nilsson.

Keywords: Emergency evacuation, tunnel evacuation, flashing lights, Theory of Affordances, way-finding, notification, emergency exit, and system design.

Abstract. A virtual reality (VR) experiment with 96 participants was carried out to provide recommendations on the design of flashing lights on emergency exit portals for road tunnel emergency evacuation. The experiment was carried out in a Cave Automatic Virtual Environment (CAVE) laboratory at Lund University. A set of variables has been 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 at 0.5 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 than 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), and reduce people's hesitation.

Brandteknik och riskhantering
Lunds tekniska högskola
Lunds universitet
Box 118
221 00 Lund

brand@brand.lth.se
http://www.brand.lth.se

Telefon: 046 222 73 60
Telefax: 046 222 46 12

Department of Fire Safety Engineering
Lund University
P.O. Box 118
SE-221 00 Lund
Sweden

brand@brand.lth.se
http://www.brand.lth.se

Telephone: +46 46 222 73 60
Fax: +46 46 222 46 12

Acknowledgements

This work is part of the “Projekt Förbifart Stockholm, studie avseende säkerhet i tunnlar”, co-funded by Trafikverket and the EU Trans-European transport network (TEN-T). The work presented in this report is a sub-part of “Projekt Förbifart Stockholm, studie avseende säkerhet i tunnlar” and it is called “Evacuation route design” (Utformning av utrymningsväg). The results presented in this report will be used to assist the design of the evacuation systems in the Stockholm bypass project by Trafikverket.

This work would not have been possible without the help of Henric Modig (Faveo Projektledning) and Anders Lindgren Walter (MTO Säkerhet). The authors thank Joakim Ericsson (Lund University) for his technical support on setting up the VR scenario in the CAVE, and Saša Kojić for his contribution on the experimental trials. The authors also wish to acknowledge Sara Petterson (MTO Säkerhet) and Andrew Pryke (Faveo Projektledning) for their support.

This document is an interim report, which summarises the main results of the research. Detailed information can be found in the final report of the project.

Co-financed by the European Union

Trans-European Transport Network (TEN-T)

Disclaimer

Table of Contents

1. Introduction

The Swedish Transport Administration (Trafikverket) is undertaking the Stockholm bypass project, a new motorway of approximately 21 km that will link the southern and northern part of the city. The Stockholm bypass project will include more than 18 km of underground motorway and it will represent one of the longest road tunnels in the world. Past fire incidents have shown that the design of evacuation routes can play a key role in the safety of road tunnel during fire emergencies. To facilitate evacuation, different way-finding installations can be used to direct evacuees to appropriate exits. However, very few systems have been tested. In particular, the use of flashing lights to mark emergency exits has been reported as a possible solution to increase tunnel safety (Nilsson, 2009). The effectiveness of way-finding installations is reflected in the likelihood of the occupants of using an emergency exit and the subsequent risk exposure in the case of fire (Ronchi et al., 2012). 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 occupant's 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.

To investigate the above mentioned variables, a Virtual Reality (VR) experiment was carried out in the Virtual Reality laboratory at Lund University. The laboratory consists of a main hall (60 m^2 with a 7 m high ceiling) and a room for development and instruction. The laboratory includes state of the art equipment in terms of Cave Automatic Virtual Environments (CAVE): The Black Box. The Black Box technology consists of a back projection system with three screen segments, each 4 m wide. In addition, an image is projected on the floor. The Black Box technology uses passive stereo with polarized light.

The purpose of the evacuation experiments is to estimate how different designs of emergency exit portals including flashing lights would perform in a road tunnel emergency evacuation. The goal is to qualitatively rank different road tunnel portal designs in the context of evacuation including different configurations of flashing lights using the VR technology.

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). This framework is used to explain perception in terms of what the object can afford people in relation to their goals. In other words, an affordance is what the object can offer (or afford) to the individuals in relation to the fulfilment of their goal. According to the theory, there are four types of affordances that are taken into consideration, namely sensory, cognitive, physical and functional affordance. The Theory of Affordances has been previously successfully employed in fire safety research to understand evacuation behaviours (Joo et al., 2013; Kim et al., 2011; Nilsson, 2009).

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. Different variables for the design of emergency exit portals in road tunnel evacuation emergencies are tested and evaluated within this research document. The results presented in this report will be used to assist the design of the emergency systems in the Stockholm bypass project. This interim report only summarises the main aspects of the study and a more detailed presentation is provided in the following report:

Ronchi E., Nilsson D., 2014. *A Virtual Reality experiment on the design of flashing lights on emergency exit portals for road tunnel emergency evacuations*. Report 3180, Department of Fire Safety Engineering, Lund University, Lund, Sweden.

2. The Virtual Reality (VR) 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.

The VR environment consists of a portion of a road tunnel based on the design of the Stockholm bypass project. 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 questionnaire based on the Theory of Affordances (ToA). 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.

Prior to running the experiments, pilot testing was performed in order to test the experimental procedure. The experiments were carried out in 14 separate days. Each day, participants took part one at a time in the scenarios including different emergency exit portal designs, which were evaluated through a questionnaire based on the Theory of Affordances.

Table 1 presents a description of the variables under consideration during the experiment and the corresponding installation setups. The selection of the specific installation setups is based on a literature review carried out by the research group before carrying out the experiment and the future practical application in the Stockholm bypass project.

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 (see Figure 1)	Strobe
	LED
	Double strobe
Layout of the lights (see Figure 2)	2 Bars
	3 lights (2 on the sides and 1 on top)
	1 light
Door design (see Figure 3)	Painted running man
	window

Schematic representation of the type of light source and the layout of the lights in the portal are presented respectively in Figure 1 and Figure 2. Figure 3 shows the VR scenarios on door design, i.e. the scenario with a window on the door or the running man.

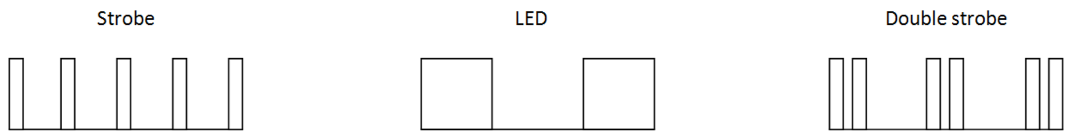

Figure 1. Schematic representation of the type (i.e., light pattern) of the light source.

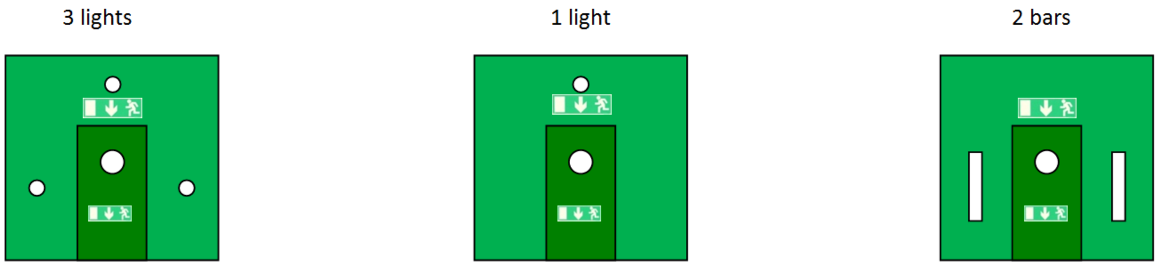

Figure 2. Schematic representation of the layout of the lights.

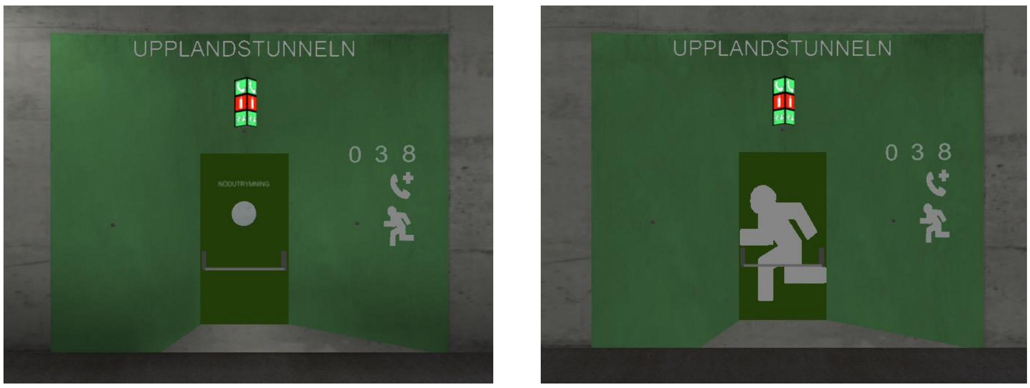

Figure 3. Exemplary representation of the VR emergency exit portal in presence of a window (left) or a running man (right) on the door.

2.1. Participants

Approximately one month before the experiments, the research group started recruiting participants via advertisements at Lund University, emails, forums, websites, and social networks. 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 to remind them the date and location of the experiments.

A total of ninety-six (96) participants eventually 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 of the ninety-six participants (90.6%) were of Swedish nationality, five participants were Danish (5.2%), two participants had double citizenship (Swedish and another citizenship) and 2 participants were not Swedish. 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 or 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 majority 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%). This is deemed to be a conservative assumption in the sample since tunnel users are not deemed to have large experience about tunnel evacuations.

In order to assess the possible impact of experience with Virtual Reality and gaming on results, two questions were made on this issue. In general, the sample includes participants with good videogame experience, with the majority 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 great majority of the participants declare to have no previous experience on Virtual Reality experiments (96.9%).

Participants who took part in the experiment were reimbursed with 200 SEK.

2.2. Experimental procedure

Participants arrived one at the time in the Virtual Reality laboratory located at the IKDC building at Lund University. The participants were asked to arrive approximately 15 minutes before the start of their experiment. On the arrival, each participant was guided to a zone of the lab (VR lab zone) separated from the CAVE lab at Lund University. Here he/she was welcomed by a researcher and provided with written general information on the experiment, including safety measures.

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. At least one researcher was always present in the CAVE laboratory during the whole duration of each VR experiment and the participants always had the right to abort the experiment at any time by contacting him. The researcher made sure that the participants understood the experiment and the safety procedures and asked if the participant needed some additional clarification. After the participant confirmed that he/she understood the information provided, he/she was asked to hand in a signed informed consent. Thereafter the participant was instructed on the overall procedure of the experiment.

The participant was then guided to the CAVE system by a 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 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 a training scenario which consisted of a labyrinth in which they 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.

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

The emergency exit portals were equipped with four different baseline 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 questionnaire based on the Theory of Affordances.

Experimental testing was hence conducted in two parts:

Experiment part 1: A set of baseline VR tunnel navigation scenarios

Experiment part 2: 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.

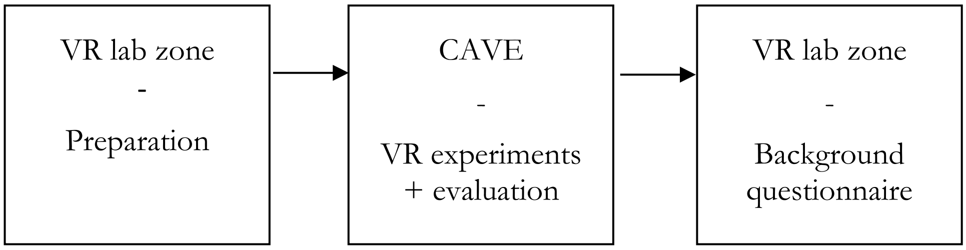

Figure 5. Flow chart of the phases of the experiment for each participant.

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.

Experiment Part 1

In this part of the experiment, test participants were asked to find his/her way out to safety in a baseline tunnel 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 has a total length of 200 m, where 100 m is the distance between the exits, which are distant 50 m from the ends of the VR scenario. The total length of the environment is longer and it includes two curves at both ends of the scenario (see Figure 7).

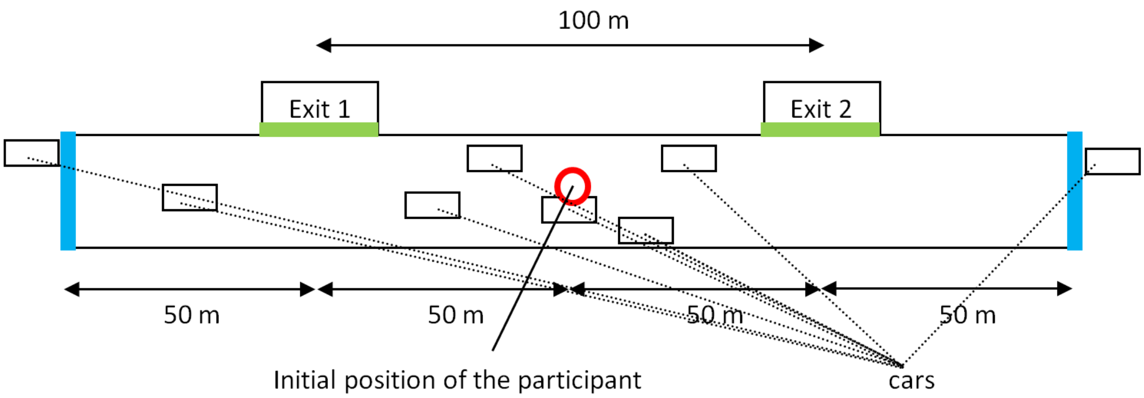

Figure 6. Schematic representation of the layout of the tunnel during the experiments. The elements within the tunnel (cars, exits, etc.) are off scale to facilitate the reading of the figure.

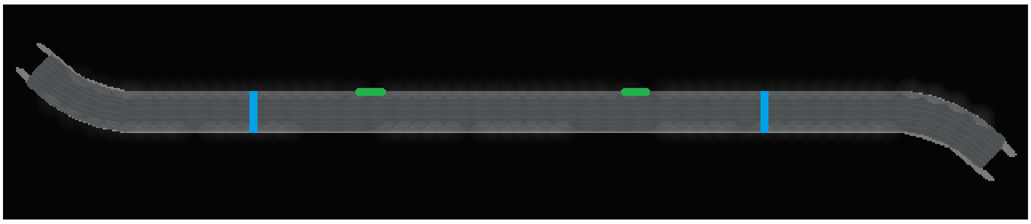

Figure 7. Schematic representation of the full VR environment. Green lines indicates emergency exits (off-scale to facilitate the reading of the figure) and blue lines indicates the end of the scenarios.

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 within a fixed amount of 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).

Experiment Part 2

After the baseline tunnel 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]

It should be noted that given the scope of this interim report, the sole results of the final question (third question) on the overall evaluation of the designs are presented and discussed.

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.

2.3. Scenarios

The baseline scenarios of experiment part 1 have 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**
1Afull	Green	1 Hz	LED	3 lights	24
2Afull	Green	2 Hz	LED	3 lights	24
3Afull	Green	1 Hz	Strobe	3 lights	24
4Afull	Green	1 Hz	LED	2 Bars	24

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 (C=1A=2B=3B=4B in Table 3 and in green) 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 the 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 parts coloured in green represent the scenarios that present the same configuration

Scenario	Variable under investigation	Colour	Flashing Rate	Type of light source	Layout and position
C=1A=2B=3B=4B	Colour	Green	1 Hz	LED	3 lights
1B		White	1 Hz	LED	3 lights
1C		Blue	1 Hz	LED	3 lights
2A	Flashing Rate	Green	4 Hz	LED	3 lights
C=2B=1A=3B=4B		Green	1 Hz	LED	3 lights
2C		Green	0.25 Hz	LED	3 lights
3A	Type of light source	Green	1 Hz	Strobe	3 lights
C=3B=2B=1A=4B		Green	1 Hz	LED	3 lights
3C		Green	1 Hz	Double strobe	3 lights
4A	Layout and position	Green	1 Hz	LED	2 Bars
C=4B=3B=2B=1A		Green	1 Hz	LED	3 lights
4C		Green	1 Hz	LED	1 light
E (Extra)	Door design with painted running man	Green	1 Hz	LED	3 lights
NO	No lights	/	/	/	/

Each participant was placed in front of seven configurations (plus the initial tunnel navigation in experiment part 1, see also Table 4). The baseline scenario C=1A=2B=3B=4B and the scenario with no lights (NO) were administered to all 96 participants. All other scenarios (1B, 1C, 2A, 2C, 3A, 3C, 4A, 4C, 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	1Afull	1A	1B	1C	No lights	extra	2A	2C
order 2	1Afull	1A	1C	1B	No lights	2C	2A	1A
order 3	2Afull	2A	2B	2C	No lights	1B	1C	extra
order 4	2Afull	2A	2C	2B	No lights	1C	1B	2A
order 5	3Afull	3A	3B	3C	No lights	4A	4C	extra
order 6	3Afull	3A	3C	3B	No lights	4C	4A	3A
order 7	4Afull	4A	4B	4C	No lights	extra	3A	3C
order 8	4Afull	4A	4C	4B	No lights	3C	3A	4A

2.4. Analysis of Likert Scale responses

Forty-eight (48) measurements have been obtained for all door designs, with the exception of the baseline (C) and the scenario with no lights (NO) for which there are 96 measurements. This means that all participants ranked the baseline and the scenario with no lights, while half of the sample evaluated the other scenarios. Given the scope of the present document, (i.e. to briefly present the main results of the study) the sole analysis of the responses to the final question on the overall evaluation of the design is presented here.

Descriptive statistics are presented in Table 5 and Figure 9. From the descriptive statistics, it is possible to observe that there are differences in the percentiles of scores for different designs. 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, i.e., the scenarios seem to present different scores.

Table 5. Descriptive statistics of the responses to the questions on the overall evaluation of the designs.

Descriptive Statistics									
Scenario Code	**Description**	**N**	**Mean**	**σ**	**Min**	**Max**	**Percentiles**		
							25th	**50th (Median)**	**75th**
C3	Baseline	96	2.42	.627	0	3	2	2	3
1B:3	White lights	48	2.31	.748	0	3	2	2	3
1C:3	Blue lights	48	1.38	1.123	-1	3	1	1	2
2A:3	Fast flashing	48	2.40	.818	0	3	2	3	3
2C:3	Slow flashing	48	1.79	.898	0	3	1	2	2
3A:3	Single Strobe	48	1.90	.831	0	3	1	2	2
3C:3	Double Strobe	48	2.04	.617	1	3	2	2	2
4A:3	2 bars	48	2.56	.580	1	3	2	3	3
4C: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

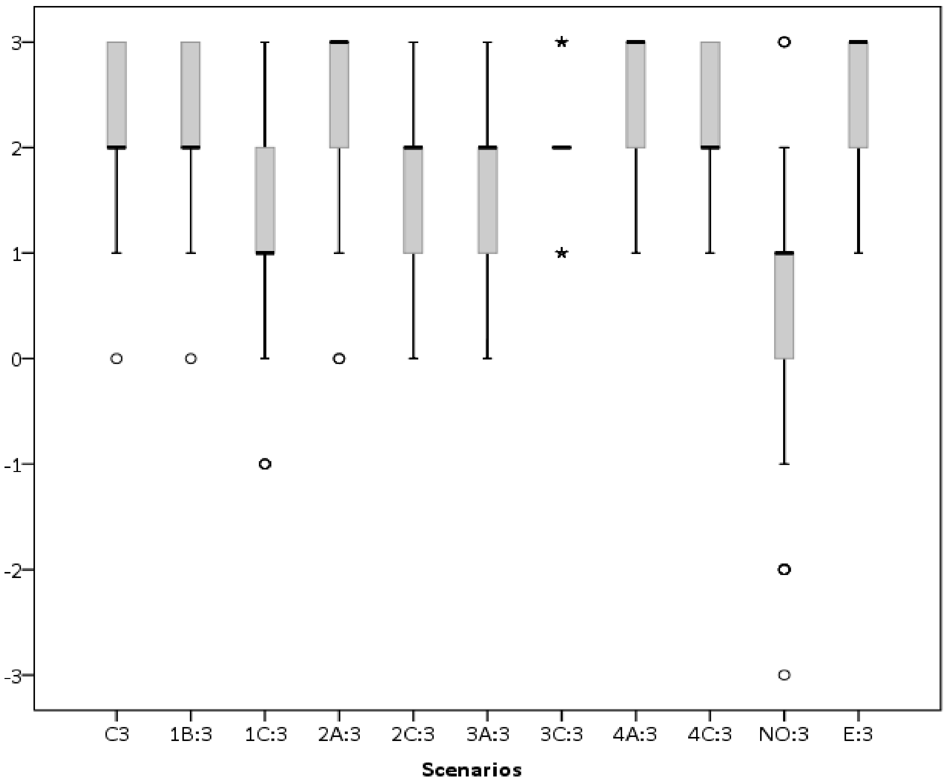

Figure 9. Boxplots of the Likert scale responses to the third questions on the overall evaluation of the designs.

In order to identify exactly where those differences are, a separate set of Wilcoxon signed-rank tests is performed on the different combinations of interest. In this case, the scenario C3=1A:3=2B:3=3B:3=4B:3 is the baseline scenario, so that the differences between the baseline and the alternative designs can be statistically evaluated. The baseline scenario is constituted by three green LED lights, with a flashing rate equal to 1 Hz. This is made by pairs of Wilcoxon signed-rank tests (one scenario is always the baseline scenario, i.e. C3 in the next Tables 6 and 7).

Table 6. Paired comparisons of all scenarios with the baseline scenario (C3).

Comparison		**N**	**Mean Rank**	**Sum of Ranks**
Baseline vs white lights (C3 vs 1A:3)	Negative Ranks	10	9.00	90.00
	Positive Ranks	7	9.00	63.00
	Ties	31		
	Total	48		
Baseline vs blue lights (C3 vs 1C:3)	Negative Ranks	32	17.19	550.00
	Positive Ranks	1	11.00	11.00
	Ties	15		
	Total	48		
Baseline vs fast flashing (C3 vs 2A:3)	Negative Ranks	6	10.17	61.00
	Positive Ranks	10	7.50	75.00
	Ties	32		
	Total	48		
Baseline vs slow flashing (C3 vs 2C:3)	Negative Ranks	23	12.61	290.00
	Positive Ranks	1	10.00	10.00
	Ties	24		
	Total	48		
Baseline vs single strobe (C3 vs 3A:3)	Negative Ranks	24	14.31	343.50
	Positive Ranks	3	11.50	34.50
	Ties	21		
	Total	48		
Baseline vs double strobe (C3 vs 3C:3)	Negative Ranks	21	12.05	253.00
	Positive Ranks	2	11.50	23.00
	Ties	25		
	Total	48		
Baseline vs 2 bars (C3 vs 4A:3)	Negative Ranks	4	7.00	28.00
	Positive Ranks	9	7.00	63.00
	Ties	35		
	Total	48		
Baseline vs 1 light (C3 vs 4C:3)	Negative Ranks	15	10.00	150.00
	Positive Ranks	4	10.00	40.00
	Ties	29		
	Total	48		
Baseline vs no lights (C3 vs NO:3)	Negative Ranks	85	44.61	3792.00
	Positive Ranks	2	18.00	36.00
	Ties	9		
	Total	96		
Baseline vs running man (C3 vs E:3)	Negative Ranks	4	7.50	30.00
	Positive Ranks	11	8.18	90.00
	Ties	33		
	Total	48		

Test statistics are presented in the next Tables 6 and 7 (in grey the cases in which significant differences are found):

Table 7. Results of the Wilcoxon tests. The parts in grey indicate scenarios which resulted statistically different than the baseline scenario.

	1B:3 - C3	1C:3 - C3	2A:3 - C3	2C:3 - C3	3A:3 - C3
Z	-.728[b]	-4.979[b]	-.393[c]	-4.258[b]	-3.976[b]
Asymp. Sig. (2-tailed)	.467	.000	.694	.000	.000
	3C:3 - C3	**4A:3 - C3**	**4C:3 - C3**	**NO:3 - C3**	**E:3 - C3**
Z	-3.922[b]	-1.387[c]	-2.524[b]	-8.061[b]	-1.886[c]
Asymp. Sig. (2-tailed)	.000	.166	.012	.000	.059

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

A Bonferroni corrections 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 per 6, i.e. corrected significance level $\alpha_c=0.0083$.

Considering the corrected significance levels, the scenarios that appear statistically different from the baseline are: 1C (blue lights), 2C (slow flashing), 3A (single strobe), 3C (double strobe), NO (no lights). This means that the baseline scenario is preferred over those scenarios (i.e. they have a higher proportion of lower scores than the baseline).

The other scenarios do not statistically differ from the baseline scenario. These scenarios include the use of white lights (1B), faster flashing rate (2A), two bars (4A), 1 light (4C), and the extra scenario with the running man (E).

These conclusions are in line with the analysis of descriptive statistics, 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.

3. 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 baseline 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.

4. References

British Standards, 2013. BS 5839-1:2013 Fire detection and fire alarm systems for buildings.

Gibson, J.J., 1986. The Ecological approach to visual perception. Lawrence Erlbaum Associates, Hillsdale (N.J.).

Hartson, H.R., 2003. Cognitive, physical, sensory, and functional affordances in interaction design. Behav. Inf. Technol. 22, 315–338.

Joo, J., Kim, N., Wysk, R.A., Rothrock, L., Son, Y.-J., Oh, Y., Lee, S., 2013. Agent-based simulation of affordance-based human behaviors in emergency evacuation. Simul. Model. Pract. Theory 32, 99–115. doi:10.1016/j.simpat.2012.12.007

Kim, N., Joo, J., Rothrock, L., Wysk, R., Son, Y.-J., 2011. Human Behavioral Simulation Using Affordance-Based Agent Model, in: Jacko, J.A. (Ed.), Human-Computer Interaction. Design and Development Approaches. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 368–377.

Nilsson, D., 2009. Exit choice in fire emergencies: influencing choice of exit with flashing lights. Dept. of Fire Safety Engineering and Systems Safety, Lund University, Lund, Sweden.

Ronchi, E., Nilsson, D., Gwynne, S.M.V., 2012. Modelling the Impact of Emergency Exit Signs in Tunnels. Fire Technol. 48, 961–988. doi:10.1007/s10694-012-0256-y