Influence of Information and Instructions on Human Behavior in Tunnel Accidents: A Virtual Reality Study

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Abstract

Human behavior is a major factor modulating the consequences of road tunnel accidents. We investigated the effect of information and instruction on drivers' behavior as well as the usability of virtual environments to simulate such emergency situations. Tunnel safety knowledge of the general population was assessed using an online questionnaire, and tunnel safety behavior was investigated in a virtual reality experiment. Forty-four participants completed three drives through a virtual road tunnel and were confronted with a traffic jam, no event, and an accident blocking the road. Participants were randomly assigned to a control group (no intervention), an informed group who read a brochure containing safety information prior to the tunnel drives, or an informed and instructed group who read the same brochure and received additional instructions during the emergency situation. Informed participants showed better and quicker safety behavior than the control group. Self-reports of anxiety were assessed three times during each drive. Anxiety was elevated during and after the emergency situation. The findings demonstrate problematic safety behavior in the control group and that knowledge of safety information fosters adequate behavior in tunnel emergencies. Enhanced anxiety ratings during the emergency situation indicate external validity of the virtual environment.

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Keywords: tunnel accidents, virtual reality, driving simulator, information, instructions, tunnel safety knowledge

1 Introduction

Accidents occur less frequently in tunnels than on open roads, but may have more severe consequences [AR00]. Catastrophic fire breakouts in European transalpine tunnels (e.g., Mont-Blanc tunnel in 1999) stimulated various studies on tunnel safety. These studies mostly increased safety through technological innovation and new safety standards, which decreased accident rates (e.g., [Amu94], [AR00]). Despite these efforts, another severe accident occurred in the Fréjus Tunnel (2005), leading to two deaths and 19 injured. Although tunnel accidents may have various reasons, human misconduct is responsible for about 95 % of all cases [Bun00] and consequently, maladaptive behavior has become the focus of recent research [Mar06]. As tunnels become longer and their use becomes more frequent, psychological research in particular is needed to gain new insights on occupant behavior in dangerous situations [FNF13].

Psychological research on dangerous situations has benefited from the recent developments of virtual reality (VR) technologies, allowing experimental control in externally valid virtual environments (VE) [BL10]. The possible applications of VR are vast. One study observed participants' responses to a fire outbreak in a virtual library and showed that participants responded deliberately rather than fleeing in panic – a study that would have been impossible in a real-life setting [GCS+03]. VR was used to study evacuation from underground railway stations [DCR+09], as well as way-finding and emergency signage [TWL09]. Calvi found that drivers inside a virtual tunnel drove more carefully and experienced more anxiety than on open roads [Cal10, CB11]. Mühlberger et al. confirmed subjective and physiological fear responses of tunnel phobic participants during virtual tunnel drives [MBWP07]. In recent VR studies, evacuation behavior during tunnel emergencies was found to be modulated by the behavior of other tunnel occupants [KMJ+14, KRG+14], however, the decision to leave the vehicle seemed not to be influenced by a co-driver [KMMP12], and the evacuation routes chosen by participants differed from those predicted by evacuation simulations [RKM+15]. VR training may also improve real world tunnel evacuation [KPM+13].

Results of validation studies of driving simulators are promising. Driving behavior in a simulated virtual tunnel was found to be comparable to driving behavior in a real tunnel [CB11, HYT07, MSW+11, SCAM09, T98̈]. Another study found comparable fire evacuation behavior from a building in VR and real world laboratory experiment [KHdVP10]. Thus, VR is as a promising tool to gain new insights in human behavior in emergency situations that otherwise would be very difficult to explore. However, it remains to be shown that virtual emergency situations induce fear reactions in participants.

Emergency situations in tunnels require adequate reactions from tunnel occupants. Reports from tunnel fires point out that self-evacuation during tunnel emergencies is problematic (e.g. [Bro02]; for an extensive overview of tunnel fires see [Mar08]). A questionnaire study found that although many occupants are aware of safety devices in tunnels, the intention to use those is not internalized [GKC09]. A field study confronting tunnel occupants with a simulated fire confirmed these questionnaire data. In this study, some participants waited over five minutes before considering evacuation, including the ones who stood right behind the fire, although such behavior would be fatal in a real emergency situation [Boe03]. The correct response - immediate evacuation - was observed only in one out of seven tests. Another tunnel evacuation experiment showed that although many occupants are aware of danger during tunnel accidents they are often not sure how to evacuate [NJF09].

Improving tunnel safety through establishing adequate behavioral knowledge in tunnel occupants seems promising. A previous study examined how information and instruction affected participants' behavioral responses in a tunnel emergency simulation [Mar06]. Participants were confronted with an accident, fire and smoke in a virtual tunnel. Two experimental groups received a leaflet containing checklists for safety behavior in a tunnel. One of these two informed groups received extra instructions via head phones during the event. A third control group received neither information nor instructions. About 60 % of the control group switched off the engine during the event; after reading the leaflet, this increased to 70 %, and with additional instructions to 100 %. Only few participants switched on the radio, and most did not do so even after reading the recommendation in the leaflet. Leaving the vehicle was associated with the verbal instructions of the operator. 65 % of the control group, but 75 % of participants who only read the leaflet and 94 % of participants who read the leaflet and heard additional instructions wanted to leave the vehicle. Specific instructions from the tunnel operating personal may be important to initiate evacuation since fire alarm bells are known to be less effective [Pro03, PS91]. Interestingly, Martens reported that some participants indicated that they would have used the tunnel portal rather than the emergency exit to evacuate, a behavior also seen in real tunnel emergencies [Sim85, Sim01]. This pattern is referred to as movement to the familiar and has been documented in a variety of emergency situations. Unfortunately, the authors did not report inferential statistics, and it remains unclear whether participants perceived the simulated accident as realistic or not. Furthermore, the study did not report how fast informed or instructed participants compared to the control group responded, yet this information is necessary to predict the impact of the emergency and/or the safety intervention.

After exploring the overall knowledge in a German sample on correct behavior in tunnels and the influence of the change in the theoretical examination for getting a driver's license, the main target was to measure actual behavior in an emergency situation. Thus, the first goal was to replicate and extend the findings of Martens and assess the impact of information and instructions on reaction latencies in emergency situations. In addition, we evaluated participants' emotional responses triggered by the simulated emergency in order to assess the external validity of the VR system. The research questions were addressed by having participants conduct three virtual tunnel drives with the following situations: traffic jam, no event, and tunnel blocked by trucks and oncoming smoke (emergency situation).

Since 2008, tunnel safety has become a mandatory part of the German theoretical road user education. This education aims to improve the general tunnel safety knowledge of the population. It remains to be shown how these efforts affected young drivers' tunnel safety knowledge. Therefore, the second goal of the present article is to investigate the general knowledge about tunnel safety.

In order to reach the two goals, two studies on tunnel safety were realized. The first investigated tunnel knowledge using an online questionnaire; the second tested the effect of information and instructions on tunnel behavior in a VR experiment. The following sections will describe the two studies followed by discussion of the results and limitations of the studies.

Table 1: Responses (%) to tunnel fire safety related items from the German theoretical driving exam

	Question	%
What should you do in case of a tunnel fire?		
1.	Try to warn other drivers*	73.0 %
2.	Look for the closest egress route*	93.6 %
3.	Alarm the tunnel surveillance center*	96.6 %
What should you do in case of thick smoke in a tunnel?		
1.	Switch off the engine*	89.2 %
2.	Look for the egress route*	97.3 %
3.	Warn other road users*	67.6 %
You notice an accident in a tunnel. What should you do?		
1.	Switch on hazard flasher*	95.3 %
2.	Inform emergency services using emergency phone*	95.3 %
3.	Do not leave the vehicle**	10.8 %

Note: Questions were provided in German. The original as well as the complete set of items is available from the authors on request, * Correct answer; ** wrong answer

2 Tunnel safety knowledge

Our first goal was to assess the general tunnel safety knowledge in the German population. To our knowledge, only one study assessed tunnel occupants' safety knowledge [GKC09]. The study of Gandit et al. assessed tunnel occupants' awareness of safety installations as well as behavioral intentions in a French speaking population (see discussion of the results above). We developed an online questionnaire comprising relevant tunnel safety information (e.g., about emergency exit location or adequate responses to fire emergencies). Since 2008, tunnel safety is part of the German theoretical driver's license education and examination. Thus, we were able to compare responses from participants who completed their driver's license before with those who received it after 2008.

2.1 Material and methods

One hundred and forty eight participants (age: $M = 29.16$, $SD = 12.78$; 69.6 % female) were recruited to complete an online multiple choice (MC) test that was made available over an online questionnaire provider (www.soscisurvey.de). Participants were recruited through mailing lists and social media.

The MC test comprised (a) questions from the German theoretical driving exam (13 items) and (b) questions derived from a brochure on tunnel safety behavior developed by the German Federal Highway Research Institute (13 items). Both parts included questions on general tunnel knowledge (e.g., what to do prior to driving into a tunnel) and specific questions on adequate behavior during tunnel emergencies (e.g., how to react to a tunnel fire).

The MC items selected from the theoretical driving exam had three response options. Participants were instructed to check all responses they thought were correct. At least one response option per item was correct. A question was counted as answered correctly only if all correct options and no wrong option were checked. If a participant did check only one of several correct options, or checked correct and incorrect options, the whole questions was regarded as answered incorrectly. This corresponds to the procedure in the German theoretical driving examination.

The items derived from the brochure had four possible response options. Participants were informed that only one of the four response options was correct. In contrast to the questions from the driving examination, participants could only select one option (it was technically impossible to check several options). The number of correct answers for each series of questions was calculated into a sum score (ranging from 0 to 13 respectively).

2.2 Results

Table 1 depicts examples of questions from the theoretical driving exam and percentage of checks. On average, 77.2 % ($SD = 16.8\,\%$) of these tunnel safety questions were answered correctly. Table 2 depicts examples of questions derived from the tunnel safety brochure of the German Federal Highway Research Institute and percentage of checks. On average, 42.8 % ($SD = 13.9\,\%$) of the questions were answered correctly. Since tunnel safety was not a part of the German theoretical driver education curriculum before 2008, we also compared participants who received their driver's license before with those who received it in or after 2008 (Figure 1). As expected, participants who received their driver's license before 2008 gave fewer correct answers to the questions taken from the German theoretical driver's license exam, $t(144) = 3.24$, $p = .001$, $d = 0.54$, but there were no differences between the two groups with regard to the number of correct answers on the MC questions derived

Table 2: Responses (%) to tunnel fire safety related items in the tunnel safety brochure of the German Federal Research Institute

Question		%
Which statement ist NOT correct?		
1.	Emergency phones can be found every 150 meters**	15.9 %
2.	Emergency phones are safe shelters in case of fire*	37.8 %
3.	Emergency sidewalks to the emergency phones are both sides of the road**	16.9 %
4.	Use of mobile phones complicates locating tunnel users**	30.4 %
Where do emergency exits lead to in road tunnels?		
1.	To the neighboring tunnel bore**	3.1 %
2.	To refuge areas/shelters**	13.2 %
3.	Out of the tunnel via separate exits/escape routes**	36.5 %
4.	Out of the tunnel via the neighboring bore and via separate exits/escape routes*	45.3 %
Where can you find emergency phones in road tunnels?		
1.	At the entrance portal and every 150 meters in longer tunnels*	52.7 %
2.	Next to emergency exits**	13.9 %
3.	Next to emergency exits and every 200 meters**	19.6 %
4.	At the entrance portals, next to emergency exits, and every 200 meters**	12.8 %
What is the usual speed limit in highway road tunnels?		
1.	60 km/h**	2.7 %
2.	80 km/h*	49.3 %
3.	100 km/h**	39.9 %
4.	120 km/h**	8.1 %

Note: Questions were provided in German. The complete set of items is available on request, * Correct answer, ** wrong answer from the tunnel safety brochure of the German Federal Research Institute, $t(144) = -0.72$, $p = .474$, $d = -0.12$.

2.3 Discussion

We examined the tunnel safety knowledge in the general population using an online questionnaire. Our results revealed on the one hand that the majority of participants showed good knowledge of tunnel safety. On the other hand it is worrying to notice that for example the majority of participants assumed that emergency phone booths can be used as safe refuge areas during tunnel fires. These results are in line with the work of Gandit, who showed that tunnel occupants may know about the existence of tunnel safety installations but may not necessarily know how to use those [GKC09]. In addition to that, the results showed that participants who were issued a driver's license in or after 2008, had better tunnel safety knowledge than those who received it prior to that date. This indicates that measures such as theoretical training on tunnel safety may improve occupants safety knowledge.

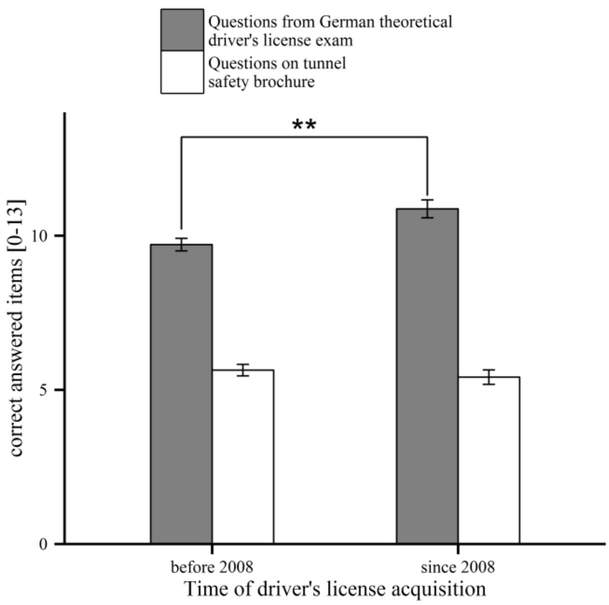

Figure 1: Number of correct answers in the two MC questionnaires on tunnel safety (Driver's license and questions from the tunnel safety brochure)

However, the results of the present study have to be interpreted with caution for several reasons. First, the two groups differed in age and driving experience. Second, it is unclear how long the effects of such theoretical interventions last especially if the acquired knowledge may potentially never be needed. Third, it is unclear, if and how theoretical tunnel safety training is translated into actual behavior. To target this question, we conducted an experimental study and tested safety behavior in a VR emergency scenario.

3 VR Study

3.1 Material and Methods

Participants

Forty-four volunteers (age $M = 24.41$, $SD = 3.27$ years, 23 female, no group differences) participated in the study and were randomly assigned into three different groups. One group (control group, $n = 15$) received neither information nor instructions. The second group (informed group, $n = 14$) read a brochure of the German Federal Highway Research Institute (Bundesanstalt für Straßenwesen, BASt) containing general information about German tunnels and relevant information about emergencies, and the third group read the same brochure and received verbal safety instructions during the emergency situation (informed/instructed group, $n = 15$). The groups did not differ in any demographic or baseline questionnaire data (see Table 3).

Apparatus

The VE was created using the VR Modelling Language (VRML) [Nad99].The virtual tunnel scenarios were controlled using the in-house written VR-simulation software CyberSession. Due to the technical and financial limitations of a social science research group we used a VR simulation system built with two main goals. First, the VR-simulation and image generation had to work with gaming-hardware components in order to reduce system acquisition and maintenance costs. Second, the graphical user interface of the simulation-software should enable non-technical staff to run the simulation and data-acquisition.

The simulation-computer, running the simulation-software, provided the experimenter with a graphical user interface to control scripted sequences of the experimental paradigm. The simulation-computer processed the data of the tracking system and the human-interface-devices, controlled the micro-motion-system and an image generator. A second computer generated the images (Intel(R) Core(TM) i7 CPU 950 @ 3 GHz, NVIDIA GeForce GTX 285) running a Cor-

Table 3: Characteristics of the three experimental groups

	Control group			Informed group			Informed/instructed group			
	n	m	SD	n	m	SD	n	m	SD	p
Driver's license										n.s.[2]
$<$ 5 years	3			3			4			
5–10 years	9			10			8			
10-15 years	3			2			2			
tunnel drives per year										n.s.[2]
$<$ 20	8			9			11			
20–49	6			5			3			
50–100	0			1			0			
$>$ 100	1			0			0			
STAI trait[3]	15	34.27	8.27	14	38.36	7.80	15	36.53	7.19	n.s.[1]
TAQ (driver version)[3]	15	3.60	4.08	14	5.93	5.03	15	4.36	3.63	n.s.[1]
TAQ (co-driver version)[3]	15	3.67	3.81	14	5.79	5.56	15	5.00	3.66	n.s.[1]

[1]Between-subjects ANOVA; [2]χ^2statistics; [3]sum scores; STAI = State-Trait Anxiety Inventory; TAQ = Tunnel Anxiety Questionnaire.

tona VRML Renderer (ParallelGraphics, Dublin, Ireland). The graphical and auditory simulation was presented using a head-mounted display with headphones. (HMD; nVisor SX, NVIS Inc., Reston, VA, USA). The viewpoint was adapted through an electromagnetic tracking device (FASTRACK, Polhemus Corp., Colchester, VT, USA), assessing head position and orientation with six degrees of freedom (DOF). Participants were seated on a moving platform with six DOF (micro-motion-system, Krauss-Maffei-Wegmann GmbH & Co. KG, Munich, Germany).

Figure 2: Screenshot from the emergency situation (contrast and brightness have been increased by 40 % for improved illustration)

Navigation was implemented using car steering elements (Logitech G25 steering wheel with gas and brake pedal). Additional hardware for switching on lights, radio, hazard-flasher, and door opener was installed on a mock-up and implemented in the VR-simulation. The car mock-up as well as the virtual car were designed to imitate a real car. To make the interaction intuitive the position of the mock-up interaction components were positioned in the corresponding position to the visual representation in the VE. For example, the door handle was to the left of the driver both in VR and the mock-up. With regard to the research questions and the development-timeframe, we limited the development of the following driving-simulation details. The mockup did not allow the use of a safety belt and did not include handles to open a window, to alter the air ventilation, to switch cab-lights or to shift gear. Navigation was restricted, to steering, driving forward and to brake in the simulation.

Measures

Relevant safety behavior defined by the BASt was provided in an information brochure and included the following behavioral patterns in case of fire or smoke in tunnels: Stop and turn off the vehicle, begin hazard-flashing, switch on the radio to receive information, and leave the tunnel.

During the tunnel drives, participants were required to rate their current anxiety verbally on a scale ranging from 0 (no anxiety) to 100 (maximum imaginable anxiety). At certain points during the drives (see procedure), a prerecorded question ('Please rate your anxiety now.') was played back and the experimenter protocolled each rating. While answering the questions participants continued to drive. Participants were familiar with this procedure due to pre-experimental training. The State-Trait Anxiety Inventory (STAI) [LS81, SGL70] and the Tunnel Anxiety Questionnaire (TAQ) [MP00] were used as control variables.

Procedure

Prior to the experiment, participants gave their informed consent and completed the questionnaires (sociodemographic information, STAI, TAQ). Subsequently, the informed group as well as the informed/instructed group participants read the tunnel information brochure provided by BASt. A written instruction then explained that the task during was to conduct several drives through a virtual tunnel on a highway and that participants should drive according to traffic rules. Instructions included an explanation on how to perform anxiety ratings during the drives. Participants practiced using all mock-up elements until they could easily handle them before being immersed into the VR. Participants had to use all mock-up (door handle, light switch, radio, hazard flasher, steering wheel) elements first with open eyes and then with closed eyes. Then they conducted a test drive in which handling the vehicle and verbal anxiety ratings were practiced. In this drive, participants had to practice once more the use of the mock-up elements.

The experiment itself consisted of three tunnel drives through. Each drive started outside the tunnel and after about 50 seconds of driving on an open road participants entered the tunnel. Participants rated their anxiety three times: First, 1 minute after entering the tunnel and twice according to the experimental drive. In the first drive, participants had to follow a car and a truck, which both stopped in the middle of the tunnel forming a traffic jam. After 1 minute, they continued driving. The drive ended after leaving the tunnel. The aim was to sensitize participants to unexpected situations. Here, the second anxiety rating was required after the other vehicles and the participant had stopped, and the third rating was assessed near the end of the tunnel. Transitions between the drives were smooth and created the impression of one continuous route. In the second drive, participants drove through the empty tunnel with no additional traffic (control drive). This drive was introduced to give an impression of a "normal" tunnel drive. Participants were asked to give the second anxiety rating in the middle and the third rating near the end of the tunnel. After leaving the tunnel and driving again on the open road for about 200 meters, the next drive started. In the third drive, there was no visible difference from the control drive at first. However, after 2 minutes of driving in the tunnel, a truck blocked both lanes (emergency situation; Figure 2). Having stopped their vehicle in front of the truck, participants were asked to rate their anxiety for the second time. One minute later, smoke started expanding from the truck. For the informed/instructed group, the pre-recorded instruction was played back in the emergency situation 25 seconds after the smoke had started ("This is an emergency. Leave the tunnel via the emergency exit."). After two minutes, participants were completely surrounded by smoke. The trial ended either if participants opened the driver's door or after additional two minutes. A few seconds later, the participants rated their anxiety for the third time. In contrast to the other ratings the last anxiety rating was not performed within the actual simulation, but directly after the emergency situation. This ensured that the rating itself did not influence participants during the event. All experimental drives were administered in the same order for all participants.

3.2 VR-study: Results

Behavioral Data

Table 5 depicts frequencies of relevant safety behavior during the event and χ^2-statistics for overall group differences. Significant differences were found for switching on the hazard flasher, turning off the engine, and leaving the vehicle (see Table 4). Follow-up tests comparing control and informed group revealed that the informed group switched on the hazard flasher more frequently, $\chi^2(1) = 6.43$, $p < .05$, but turned off the engine equally frequent, $\chi^2(1) = 1.77$, $p = .18$. Importantly, the informed group left the vehicle more often than the control group, $\chi^2(1) = 11.63$, $p < .01$. Follow-up comparisons between the informed and the informed/instructed group showed that the informed/instructed group turned off the engine more often, $\chi^2(1) = 11.84$, $p < .01$; however, participants from both groups switched on the hazard flasher and left the vehicle equally often, $\chi^2(1) = 4.55$, $p = .06$ and $\chi^2(1) = 2.30$, $p = .12$.

Since driving experience and gender are known to influence occupant behavior, the possible influence of

Table 4: Characteristics of the three experimental groups

Latency [sec] from...	Control group n	m	SD	Informed group n	m	SD	Informed/instructed group n	m	SD	p
See event to stop vehicle	15	18.85	6.81	14	18.98	5.42	15	18.32	5.76	.95
See event to switch on hazard flasher	6	20.05	4.71	12	21.72	12.41	8	17.73	7.10	.68
See event to switch on radio	2	87.95	35.91	5	169.18	64.78	6	106.06	14.33	.05
Stop vehice to turn off engine	3	51.06	48.48	15	45.63	28.53	6	31.81	8.97	.24
Stop vehicle to leave vehicle	3	100.40	9.72	12	86.80	9.54	15	92.95	11.39	.11

[1]Between-subjects ANOVA

these variables on participants' flight behavior was controlled [Mar08]. Neither the participants' gender, $\chi^2(1) = 0.49$, $p = .48$, nor the number of tunnel drives per year, $\chi^2(1) = 0.77$, $p = .68$, nor the years of having a driver's license, $\chi^2(1) = 2.56$, $p = .27$, had any influence on how often participants left the vehicle during the event.

Table 5: Frequencies of relevant safety behaviors of the three experimental groups during the emergency event

Action	CG n	IG n	IIG n	χ^2	p
Hazard flash on	6	12	8	12.31	$< .01$
Radio on	2	5	6	2.94	.230
Engine off	3	6	15	19.54	$< .001$
Leave vehicle	3	12	15	24.70	$< .001$

CG = control group; IG = informed group; IIG = informed and instructed group

Latencies of relevant safety behaviors were defined as time (in seconds) from seeing the event (truck blocking the tunnel) to stopping the vehicle, switching on the hazard flasher, and turning on the radio. However, the latency for turning off the engine and leaving the vehicle was calculated by subtracting the time the driver had stopped the vehicle to turning off the engine and opening the door of the vehicle from the reaction time (Table 4). No differences in the response latencies were found after adjusting significance level for multiple tests (Bonferroni; $p_{\text{adj.}} = .001$). Note that only few participants in the control group showed safety behaviors, reducing the statistical power of this analysis.

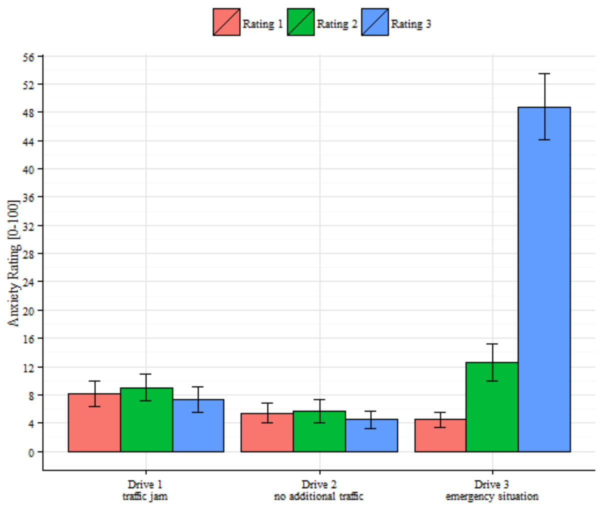

Figure 3: Anxiety ratings during the three experimental drives. Enhanced anxiety was measured after participants stopped in front of the accident (second rating in the third drive). Highest anxiety was measured after the emergency (third rating in the third drive) after participants had been fully surrounded by smoke.

Anxiety scores

Anxiety ratings assessed during each of the three drives were analyzed with separate repeated-measures ANOVAs with the between-subjects factor groups (informed, informed/instructed, control group) and time of rating during the drives (see Figure 3). No effects of time of rating or group were found in the first and second drive (all $ps > .10$). In the third drive, we found a significant main effect of time, $F(2, 82) = 84.67, p < .001$, but no effect of group, $F(2, 41) = 0.60, p = .55$. Contrasts verified enhanced anxiety ratings after participants had stopped the vehicle, $F(2, 41) = 16.49$, $p < .001$, and after the event, $F(2, 41) = 99.06$, $p < .001$, compared to the anxiety experienced at the beginning of the drive in the empty tunnel (Rating 1 at Drive 3, see Figure 3).

4 Discussion and conclusions

This study examined the effect of information and instructions on safety behavior in a simulated tunnel emergency. Three groups conducted each three drives through a tunnel in a driving simulator. Reading the information brochure had a significant effect on safety behavior. Informed participants switched on the hazard flasher, turned off the engine, and left the vehicle more frequently than the control group. Participants who received additional instructions showed similar behavioral responses. There were no differences between the two informed groups with one exception: Informed/instructed participants turned off the engine more often than informed only participants. Larger sample sizes might be necessary to reveal other highly relevant effects with medium or small effect sizes. It is important to empirically validate the effectiveness of measures aiming to improve occupant behavior, even if it seems straightforward to assume positive effects such as in the present study. For example, the information brochure was relatively long (15 pages) and contained a lot of information. Not all of this information was safety relevant. We demonstrated that readers are able to extract and apply relevant information. Participants were mostly students and in a laboratory setting. That is, they were highly educated expert readers who probably expected to be tested on the content of the brochure. One may speculate that a shorter brochure focusing only on the relevant safety information might be a more apt to convey information to the general public.

Furthermore, the control group showed mostly inadequate responses to the emergency situation. These results indicate that few uninformed participants have appropriate knowledge about adequate safety behavior in tunnel emergencies. This underlines once more the importance of studying behavior in tunnel fires, given the possible dramatic consequences [Mar08].

Regarding response latencies, we observed no differences between the three groups. However, only 3 out of 15 participants of the control group left the vehicle in the emergency situation. Therefore, group comparisons using inferential statistics were impossible. Further studies should investigate the possible effect of information and instructions on response latencies with larger sample sizes.

It is important to note that participants in the informed groups did not follow all recommendations and only few informed/instructed participants switched on the radio. Martens also found similar behavioral patterns [Mar06]. Informed participants may simply have forgotten the information about the radio. More likely, participants did not judge the act of switching on the radio as safety relevant. Further investigations should consider this aspect.

Drivers in our study were confronted with the emergency situation alone in the vehicle and no other bystanders. In a real tunnel fire, it is very likely that several people would be present. Reports from real fires as well as field and laboratory studies revealed that people in emergency situations form groups very quickly and influence each other [DL68, Mar08, NJF09]. Possible group effects could be either beneficial, e.g. occupants helping each other finding an emergency exit, or detrimental, e.g. passivity of others inhibiting decision to evacuate.

Our simulation included visual and auditory simulation of a tunnel emergency. However, a real tunnel fire is also characterized by the smell of smoke and burning materials as well as by the heat of the fire. Future studies on tunnel safety should include olfactory simulations and, if possible, heat simulations.

Participants were seated in a motion-simulator seat and wore an HMD. This reduced the ease of head-movement and limited the participants' possibilities to control the vehicle. The setup did also not allow exploring the situation outside the vehicle as the simulation was ended if the driver's door opener was activated. Although, it was not possible to study tunnel evacuation behavior holistically, VR provides the unique possibility to investigate specific aspects of the evacuation procedure individually. For example, another study assessed the behavior in tunnel emergency situations while being outside the vehicle [KRG+14]. Furthermore, an adapted version of the VE used in the present study which allowed leaving the vehicle, exploring the situation and entering the emergency exit room was developed into a training tool [KPM+13]. Reports from tunnel fires indicate that drivers often turn their vehicles and escape the same way they had entered the tunnel [Mar08]. The driving simulation used in the present study did not allow driving backwards and consequently turning the vehicle was not possible. This clearly limits the realism of our driving simulation. We suspect that at least some participants would have turned around and driven back to the portal. The external validity of VR studies is crucial and refers to the question whether the results of an experiment can be generalized. Compared to other empirical methods in tunnel evacuation research (e.g., field studies), VR allows controlling confounding variables and thus studying general underlying processes of human behavior in tunnel emergencies. No other method, not even classical laboratory studies in the physical environment, can simulate fire emergencies with the same amount of realism while still having the complete control over the experimental procedure and not putting participants' safety at risk.

Although the validity of simulators regarding driving behavior has been demonstrated, e.g. [T9̈8] or [SCAM09], it is not possible to assume external validity of all driving simulations and especially not for simulations of emergency situations. In the present study, external validity is reflected in stress reactions triggered by the simulated emergency situation. Although the simulated emergency was objectively not dangerous, the participants' anxiety ratings during the emergency situation were substantially higher than those given during the control drives, indicating that participants actually experienced the potential danger. In addition, there were no between group differences in anxiety. One may have speculated that informed participants expected a tunnel emergency, since they had read information about such an event prior to the experiment. This may provide further indication that participants found the VE as sufficiently immersive. We conclude that the used cost-effective VR setup is usable and the implemented scenario has sufficient external validity for simulating emergency situations and investigating human behavior in such situations.

In summary, this study demonstrated the effect of information on occupant behavior in a simulated emergency situation tested after the information was given. Future studies should examine further effects of instruction and long term effects of information in a larger sample size. If the sustainability of such interventions can be shown, the development of information campaigns could be a powerful preventive measure.

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