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Abstract
Fire accidents and evacuation experiments have revealed that people often use familiar exits in fire emergencies. However, the design of emergency exits has also been shown to impact people's choice of exit. In the present research, the use of flashing lights to direct people to emergency exits is explored in a series of experiments in both buildings and road tunnels. Recommendations concerning how the system should be designed are developed based on the results. In addition, a framework (Theory of Affordances) is used to explain and interpret the empirical findings and a research strategy for testing and developing evacuation systems is proposed.

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Summary

The safety of occupants in the event of fire relies heavily on their behaviour, e.g., how they respond and choose escape route. One aspect that is important for the outcome is the exit choice. Investigations of previous fire incidents and evacuation experiments have revealed that people often choose familiar exits, e.g., the everyday entrances or exits, instead of unfamiliar emergency exits. This tendency can lead to non-optimal use of exits and unnecessarily long evacuation time. One possible way to influence exit choice is to use an evacuation system, such as flashing lights at emergency exits.

The present research explores the use of flashing lights at emergency exits in both buildings and road tunnels in a series of experiments. More specifically, it investigates how the system is perceived and how it influences exit choice. Important design aspects are also identified and investigated. Recommendations are developed based on the empirical results. In addition, a framework (Theory of Affordances) is used to interpret the findings and a research strategy for developing and testing evacuation systems is proposed.

The findings suggest that flashing lights at emergency exits can influence exit choice, but also that environmental factors should be considered when the system is designed. Green appears to be the most appropriate colour of the lights because it is associated with things that are positive in emergencies, e.g., *safety* and *emergency exit*. It is recommended that the lights be placed next to the emergency exit sign to attract attention to the sign which informs people about the exit. Furthermore, the lights should begin to flash on activation of the fire alarm. This transition, together with the continued flashing, makes the exit easier to notice and is believed to signal to people that it should be used.

The Theory of Affordances is not only a useful framework for interpreting the empirical findings of the research, but is also considered appropriate for examining the design of emergency exits. The theory focuses on how the exit supports the users to achieve their goal, e.g., to escape safely, by providing different affordances. A systematic exploration of the affordances provided by an exit can reveal potential design faults early in the design process.

Finally, it is proposed that future evacuation systems be developed according to a research strategy that relies on experiments. By going through the process of (1) identifying design problems, (2) solving the problems and (3) testing the system in the field, it is possible to develop a system that works as intended. It is also recommended that the process be repeated multiple times in order to obtain the optimal design. Because the proposed strategy involves experiments with human participants, it is important to carefully consider ethical aspects.

Sammanfattning

Personsäkerheten i händelse av brand är i stor utsträckning beroende av hur personer agerar, t ex hur de reagerar och vilken utrymningsväg de väljer. Vägvalet är en aspekt som är speciellt viktig för utfallet. Utredningar av inträffade bränder och analyser av utrymningsförsök har visat att personer ofta väljer bekanta utgångar, t ex de vanliga in- och utgångarna, istället för obekanta nödutgångar. Detta beteende kan leda till att utgångarna inte används optimalt, vilket gör att utrymningen tar onödigt lång tid. Ett sätt att påverka vägvalet är att använda ett aktivt utrymningssystem, t ex blinkande lampor vid nödutgångarna.

I avhandlingsarbetet undersöks blinkande lampor vid nödutgångar i en serie försök. Mer specifikt undersöks hur systemet uppfattas och hur det påverkar vägvalet. Även för systemet viktiga designaspekter identifieras och utforskas. Rekommendationer tas fram baserat på studiens resultat. Dessutom används ett ramverk (Theory of Affordances) för att tolka resultaten och en strategi för utveckling av framtida system presenteras.

Resultaten visar att blinkande lampor vid nödutgångarna kan påverka vägvalet, men också att omgivningsfaktorer, t ex social påverkan och lokalkännedom, är viktiga att ta hänsyn till. Enligt resultaten bör gröna blinkande lampor användas, eftersom grönt ofta associeras med saker som är positiva vid nödsituationer, t ex *säkerhet* och *nödutgång*. Det rekommenderas att de blinkande lamporna placeras bredvid en utrymningsskylt, eftersom de då drar uppmärksamhet till skylten som upplyser personerna om att utgången finns. Dessutom bör lamporna börja blinka när brandlarmet aktiverar. Det faktum att lamporna börjar blinka vid aktivering av larmet leder till att utgången blir lättare att upptäcka och tros kunna signalera till utrymmande att utgången ska användas.

Det använda ramverket (Theory of Affordances) anses inte bara vara värdefullt för att tolka resultaten i följande studie, utan kan även användas för att studera utformningen av nödutgångar. Teorin fokuserar på hur utgången hjälper personer att uppnå sina mål, t ex att utrymma. Genom att systematiskt studera vad utgången erbjuder (affordances) kan potentiella brister i utformningen upptäckas i ett tidigt stadium av designprocessen.

Avslutningsvis förslås en strategi som kan användas för att utveckla nya utrymningssystem. Strategin bygger på en trestegsprocess där potentiella problem identifieras, problemen löses och systemet testas. Det rekommenderas att processen upprepas flera gånger för att uppnå den mest optimala utformningen av systemet. Eftersom den föreslagna strategin bygger på försök med människor är det viktigt att ta hänsyn till etiska aspekter.

Preface

Some years ago, I set out on a journey into the research field of human behaviour in fire. At that time, it was a field that I was not familiar with. I remember that I had many unanswered questions that I was keen to find the answers to. Now, when I am at the end of my PhD studies, I seem to have even more questions. It is with great enthusiasm that I look forward to finding the answer to these new questions and, in the process, discovering even more unanswered questions.

My journey would not have been possible without the assistance and support that I have received along the way. I would therefore like to take the opportunity to thank the people who have made my journey possible. First, I would like to thank my four financial sponsors (Brandforsk, Räddningsverket, Vägverket and Byggrådet), who have funded one paper each. This financial support has made it possible for me to perform the present research about flashing lights at emergency exits.

I am greatly indebted to my assistant supervisor Håkan Frantzich for all his support. Håkan has always provided good advice and guidance, and it has been very stimulating to work together with him in various research projects. He has also kept me on track by helping me focus on relevant aspects. I would also like to thank my former main supervisor Göran Holmstedt, who has taught me critical thinking and to work independently, and my present main supervisor Patrick van Hees, who has provided excellent support in the final year of my studies. I am also grateful for the support that I have received from our head of department Robert Jönsson. Robert has created a fantastic work environment that helps people develop both as researchers and teachers.

I would like to thank my paper co-authors Maria Johansson and Wendy Saunders. It has been rewarding to work with both Maria and Wendy because their background in psychology is quite different from my own background in engineering. I also thank Wendy for all her advice, help and encouragement during my studies. Wendy, who introduced me to the Theory of Affordances, has been a source of great inspiration.

A number of people have also helped out with the experiments and I thank them for their interest and involvement. In particular, I thank Sven-Ingvar Granemark for always helping me when I needed his technical expertise. I would also like to thank everyone who has read and commented my thesis, such as Birger Swahn whose knowledge of English grammar never ceases to amaze me.

Finally, I would like to thank my family and friends for all the encouragement that I have received throughout the years. Especially, I thank my wife Anna for standing by my side and for patiently waiting for me to finish my PhD, and my son Gustav for showing me the miracle of life.

Lund, 30 March 2009

Daniel Nilsson

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1 Introduction

Built structures, i.e., buildings and non-building structures (tunnels, bridges, etc), offer many benefits for society. For example, buildings provide shelter from the environment and tunnels facilitate efficient transportation. However, the enclosed nature of many built structures also means that the consequences of fire for occupants may be devastating. Because smoke and fire gases can accumulate inside enclosed buildings and non-building structures, conditions can quickly become dangerous. Sometimes fire leads to injuries or loss of life resulting in headlines in the media. This is particularly the case for fires that result in many fatalities, such as the Göteborg nightclub fire (Statens haverikommission, 2001) or the Mont Blanc tunnel fire (Duffé & Marec, 1999). These fire accidents receive immense media coverage and are also subject to official investigations. One explanation for the extensive attention paid to fatal fires is that they are seen as unacceptable. When people enter a built structure they expect to remain unharmed and also to be able to exit safely irrespective of any fire.

A prerequisite for successful escape from fire in built structures is that occupants are provided with adequate evacuation opportunities. Both the structure and evacuation systems, e.g., fire alarms and signage, have to be designed in a manner that promotes efficient evacuation in the event of fire. In order to improve conditions for occupants it may be appropriate to introduce both passive and active measures.

A passive measure is one that is static, i.e., that does not change in the event of fire. One example is an emergency exit, which is always present and does not require activation. Signage, e.g., standard emergency exit signs, can also be seen as a passive measure.

An active measure is one that is dynamic, i.e., that changes or is activated in the event of fire. Many active measures are also evacuation systems, i.e., systems that directly facilitate escape from fire by aiding, for example, way-finding or decision making. One of the most common examples of an active evacuation system is a fire alarm, which is triggered either manually or automatically when a fire is detected. Another example is flashing lights at exits, which have been proposed as a way to influence people's choice of exits in emergencies (McClintock, Shields, Reinhardt-Rutland, & Leslie, 2001). This type of active evacuation system may significantly improve the evacuation opportunities for the occupants.

The desire to protect occupants has led to the development of legislation on fire safety in built structures. A large portion of the legislation is focused on buildings and road tunnels, which are the two types of structures that are

included in the present research. Fire safety design of buildings in Sweden is governed by the Swedish building regulations (BFS 1993:57). According to the regulations it is possible to use either a prescription-based or performance-based approach, see Lundin (2005) for a detailed description. A prescription-based approach relies on detailed design requirements that must be fulfilled (Boverket, 2006). Two examples of common requirements are the maximum distance to emergency exits and the exit width. The main benefits of a prescription-based approach is that it is cost-effective and easy to apply, but the disadvantage is that it is inflexible. The approach is typically not appropriate for complex buildings, nor can it adequately consider the effects of installing active evacuation systems to improve fire safety.

A performance-based approach provides more freedom with regards to the building design. The approach relies on performance criteria that must be fulfilled, but it does not specify exactly how a building should be designed. One example of such a criterion is that evacuation must be completed before conditions inside the building become critical for the occupants (Boverket, 2006). This type of general performance criteria means that the approach is suitable for alternative building designs and can adequately consider the benefits of new systems. Performance-based fire safety design may hence enable the use of active evacuation systems that influence exit choice to compensate for long distances to evacuation exits. These types of compensating measures can potentially save money without endangering the safety of the occupants. However, adequate performance-based design requires knowledge about the effectiveness of such systems.

Active evacuation systems are not only useful in buildings, but can also improve the safety for motorists in road tunnels. According to the Swedish legislation on safety in tunnels, which is based on Council Directive (EC) 2004/54/EC, exemptions from some of the legal requirements are permitted if safety is not impaired (SFS 2006:421). This means that new systems can replace other safety features, which may result in a more optimal use of funds. There is also reason to believe that active evacuation systems can be particularly effective in road tunnels. Previous accidents, such as the Mont Blanc and Tauern tunnel fires, have shown that people are sometimes reluctant to leave their vehicles (Shields, 2005), which suggests that motorists may require additional prompting. One possibility is therefore to install active evacuation systems that clearly signal a change and let people know that they must evacuate. The present legislation only requires variable information signs that can inform motorists about a fire (BFS 2007:11). However, other active evacuation systems can potentially provide more potent stimuli, e.g., powerful acoustic signals or flashing lights at emergency exits. Increased knowledge of

the effectiveness of such systems in tunnel settings can therefore lead to improved fire safety in future road tunnels.

Apart from being useful for design of new buildings and road tunnels, active evacuation systems may also help to improve fire safety in existing built structures. Real fires and evacuation experiments have shown that people often use familiar exits during evacuation (Frantzich, 2001b; Sime, 1985). The tendency to move towards the familiar, e.g., people or places, in potential fire entrapment settings has been termed affiliation by Sime (1984; 1985). Movement towards familiar exits is exemplified by evacuation experiments at IKEA stores that were performed by Frantzich (2001a; 2001b). Frantzich discovered that customers seldom use emergency exits and usually escape through the everyday entrances or exits. This means that evacuation of stores may take longer than necessary, which can contribute to unnecessary exposure to smoke and fire gases in the event of fire. One possible way to avoid this problem is to use active evacuation systems to influence people to escape through emergency exits. The potential effectiveness of such systems has been demonstrated by Shields and Boyce (2000) who discovered that exits that open automatically on activation of the fire alarm, i.e., an active evacuation system, seem to be used more than other emergency exits.

It may seem reasonable that active evacuation systems can improve the fire safety of buildings and road tunnels, but is it necessary to perform research to investigate the performance of such systems? Is it not self-evident how the systems should be designed in order to be effective in the event of fire? For example, it seems a logical assumption that flashing lights at emergency exits can influence people's choice of exit. In order to be distinguishable through all types of smoke, the colour of the lights should be red, since the long wavelength of red light means that it is often scattered significantly less by small particles than many other visible colours with shorter wavelengths (Beeson & Mayer, 2008). In bright conditions, however, the eye is most sensitive to light with a wavelength of around 555 nm, which corresponds to a yellowish green colour (Judd & Wyszecki, 1975). Certain colours are also known to have established meanings within populations (Wickens & Hollands, 2000). Green is often associated with *safety* or *go*, whereas red is associated with *danger* or *stop*. A red light might therefore discourage people from using an exit whereas green might be encouraging. However, it should be added that approximately eight percent of men and one percent of women have hereditary red-green colour blindness (Nationalencyklopedin, 2008). Furthermore, it has been suggested that blue is a good colour in some countries because people associate blue with the emergency services (McClintock et al., 2001). However, the short wavelength of blue light means that it is scattered more by small particles than other visible colours (Beeson &

Mayer, 2008) and could hence be more difficult to distinguish through smoke. The examples above, which only relate to one of many design aspects, clearly illustrate that is not self-evident how an active evacuation system should be designed.

Insufficient knowledge about human behaviour and active evacuation systems in the event of fire may lead to inaccurate assumptions, which can give rise to inappropriate recommendations and unsuitable system design. As has been pointed out by Sime (1984), many old building regulations and guidelines are based on the assumption that panic can easily occur in the event of fire. It was also previously believed that panic can result in an undisciplined rush for exits that leads to trampling or crowd crush (Phillips, 1951; Roytman, 1975). In addition, it was sometimes assumed that information about the fire accident, such as the use of the word *fire* (Croker, 1917; Roytman, 1975) or over-hearing of a telephone call to the fire brigade (Home Office, 1934), may easily cause panic. This suggests that information to participants should be restricted. Restriction of information has direct implications on the design of active evacuation systems. For example, a recommendation to limit information about the fire accident may lead to voice alarms that do not mention the cause of the alarm, i.e., that a fire has been detected. However, recent research has revealed that mention of fire in voice alarms has a positive effect compared to not mentioning the cause of the alarm (Nilsson & Frantzich, in press). More specifically, mentioning fire seems to make people remember the content of voice alarms more accurately, without leading to panic and an undisciplined rush for exits. The example clearly illustrates that insufficient knowledge and presumptions may lead to a non-optimal design of active evacuation systems. It is therefore essential to base the design of such systems on systematic research that aims to explore how the system is perceived and how it influences human behaviour in the event of fire.

The development of an active evacuation system can potentially benefit from a clear theoretical framework. One example of a framework that has been used to analyse the design of emergency exits is the Theory of Affordances (Sixsmith, Sixsmith, & Canter, 1988). The theory was introduced by Gibson (1978) to explain how people perceive things that they see. According to Gibson, people perceive objects in terms of what such objects can offer or afford. For example, people will not simply see an emergence exit as a door with a sign, but instead as a means of achieving their goals. One goal, of possibly many, in a fire emergency is probably to escape safely. Emergency exits should therefore support the achievement of this goal by being easy to see, understand and use. The Theory of Affordances has been further developed by Hartson (2003) who proposed a way of analysing a design in terms of how it supports different activities. This type of structured analysis

can potentially be useful for discovering inappropriate design aspects of an active evacuation system.

One major threat to safe evacuation in the event of fire in buildings and road tunnels has been clearly identified in the present chapter, namely the tendency of people to move towards the familiar in the event of fire in built structures. This tendency, which is often termed affiliation, has been shown to lead to non-optimal use of exits. It has been suggested that exit choice can be influenced by active evacuation systems and one system that has been proposed is flashing lights at emergency exits. The design of flashing lights at emergency exits should ideally be based on systematic research, since insufficient knowledge and presumptions may lead to inappropriate system design. If adequately designed, the system can help to improve fire safety in many existing buildings and road tunnels. Similarly, knowledge about the effectiveness of the system can be useful for performance-based fire safety design by allowing alternative and cost-saving designs of future built structures.

1.1 Research objectives

The previous section has identified a number of problems relating to evacuation in the event of fire that can potentially be solved with active evacuation systems. In order to address these problems, the present research will explore the use of flashing lights at emergency exits in both buildings and road tunnels by investigating how the system is perceived and how it influences human behaviour, i.e., the choice of exit. Important design aspects of the studied system will also be identified and investigated. The research is based on the following three objectives:

i) The first objective is to develop recommendations that describe how flashing lights at emergency exits should be designed. These recommendations should be based on the research contained in the present thesis and other relevant studies.

ii) The second objective is to provide a framework for understanding and analysing the findings of the research. This framework should not only be applicable to flashing lights at emergency exits or active evacuation systems, but also to exit design in general.

iii) The third and final objective is to recommend a research strategy, i.e., combination of research methods and data collection techniques, that can be used for future testing and evaluation of evacuation systems. This strategy should also be used in the present research to explore flashing lights at emergency exits. An essential requirement is that the proposed approach be both methodologically and ethically sound.

1.2 Limitations

All studies contain limitations and the present research is no exception. Identification of relevant limitations is essential for correct interpretation and understanding of the findings. This research is associated with some limitations that are considered particularly relevant and therefore deserve mention.

The first limitation is that the research focuses on a single active evacuation system, namely flashing lights at emergency exits. This system is one of numerous systems that can influence exit choice in fire emergencies. There are also many other ways to make emergency exits more attractive, such as passive measures, but limited consideration is taken of such aspects in the present research. Flashing lights at emergency exits should therefore be seen as one way to influence exit choice. Ideally, exit design in buildings and road tunnels should not rely on only one system or approach, but instead different solutions should be combined to produce a sustainable design. Flashing lights at emergency exits, although a useful system, is hence not a substitute for appropriate exit design.

The second important limitation is related to the external validity of the findings. Although the research aims to develop general recommendations for the design of flashing lights at emergency exits, it still has to be based on studies in specific settings, e.g., experiments in specific building types with certain participant populations. For example, the present research is performed in Sweden and the findings are therefore most applicable for Swedish buildings and road tunnels, but the results are most likely also valid in many other countries. Also, for natural reasons it is not possible to include all types of buildings and road tunnels in experiments or case studies. In spite of these limitations, the research can reveal universal trends about the studied system that can be used to develop general design recommendations. However, care should always be taken when applying these types of recommendations to ensure that they are not used outside their area of application.

Finally, flashing lights at emergency exits can be designed in a variety of different ways. Each of these alternatives may potentially accomplish the task of directing people to often unfamiliar emergency exits. However, it is only possible to explore a few of the innumerable design aspects in any given study. The present research will therefore focus on those aspects that are identified as important in the research process. These aspects will naturally influence the recommendations given, i.e., suggestions of how flashing lights at exits can be designed. Although adherence to such recommendations should produce a system that can influence people's choice of exit in the event of fire, it cannot be ruled out that there may be equally effective alternative designs.

1.3 Outline of the thesis

The present thesis consists of six chapters and one appendix. In the Appendix (Appendix - Papers), the four papers that form the empirical basis of the research are given. These papers focus on exploring different aspects of flashing lights at emergency exits in both buildings and road tunnels. In the chapters, the empirical findings of the papers are summarised and put in relevant context. The chapters also give an overview of the entire research process, e.g., methodological and ethical considerations.

In Chapter 1 (Introduction), the research problem is highlighted based on Swedish legislation and previous studies. The first chapter also contains the research objectives and relevant limitations. The outline of the thesis is explained and relevant publications are given in the final part of Chapter 1.

In Chapter 2 (Methods), different research methods for studying human behaviour in the event of fire and evacuation are described and discussed. The chapter also includes a discussion of common data collection techniques. Potential strengths and weaknesses of the methods and techniques are also pointed out in relation to the objectives. Chapter 2 concludes with a description of the chosen research strategy, i.e., the combination of methods and techniques, and an explanation of how the four papers are connected.

Chapter 3 (Ethics) deals with ethical aspects of the chosen research strategy. The main question that the chapter seeks to answer is whether the used methodology is ethically viable. Measures that have been taken to reduce risks and minimise violations are also highlighted. Although ethics has been important throughout the research process, ethical considerations have not been thoroughly treated in the four papers. The third chapter should therefore be seen as an addition that goes beyond the material covered in the papers.

In Chapter 4 (Flashing lights at emergency exits), flashing lights at emergency exits are discussed in relation to relevant studies and the empirical findings, i.e., the four papers. The chapter focuses on design aspects of the studied system and environmental factors. A framework for understanding and analysing the findings, namely the Theory of Affordances, is also described.

Chapter 5 (Conclusions) contains the conclusions. The chapter also briefly summarises the design recommendations for flashing lights at emergency exits. Finally, suggestions for how the research related to active evacuation systems can be continued are given in Chapter 6 (Future research).

1.4 Publications

The present thesis is mainly based on the four papers that are presented in the Appendix. However, the author has also been involved in research on other aspects of fires and human behaviour, such as the design of voice alarms and social influence in the event of fire. Some of this research is highly relevant for the study of flashing lights at emergency exits and results from those studies are therefore referenced in the thesis. The following sections include references to both the thesis papers and related publications. In addition, the degree of responsibility and work effort of the author for the different stages of the four papers is given.

1.4.1 Thesis papers

The four papers of the present thesis have been submitted and accepted to either scientific journals or conferences. All papers have also been subject to peer-review. An extended abstract has been reviewed for one of the papers (Paper I), and three papers have been reviewed in full (Paper II, III and IV). The four papers of the thesis are:

Paper I — Frantzich, H., & Nilsson D. (2004) Evacuation experiments in a smoke filled tunnel. *Proceedings of the 3rd International Symposium on Human Behaviour in Fire*, Belfast, UK, pp. 229-238.

Paper II — Nilsson, D., Frantzich, H., & Saunders, W. (2005) Coloured flashing lights to mark emergency exits – Experiences from evacuation experiments. *Fire Safety Science – Proceedings of the 8th International Symposium*, Beijing, China, pp. 569-579.

Paper III — Nilsson, D., Johansson, M., & Frantzich, H. (2009) Evacuation experiment in a road tunnel: A study of human behaviour and technical installations. *Fire Safety Journal, 44*(4), 458-468.

Paper IV — Nilsson, D., Frantzich, H., & Saunders, W. (2008) Influencing exit choice in the event of a fire evacuation. *Fire Safety Science – Proceedings of the 9th International Symposium*, Karlsruhe, Germany, pp. 341-352.

The author of the present thesis has taken an active part in all steps of the four papers. Table 1.1 shows an estimate of the degree of responsibility and work effort of the author for the different steps of each paper. The degree of responsibility and work effort has been divided into three categories according to the following:

minor — The author has taken minor responsibility and performed a small proportion of the work (less than 1/3 of the responsibility and work effort)

medium — The author has taken medium responsibility and performed approximately half of the work (between 1/3 and 2/3 of the responsibility and work effort)

major — The author has taken major responsibility and performed a large proportion of the work (more than 2/3 of the responsibility and work effort)

Each paper can be divided into five consecutive steps according to Table 1.1. Step 1, which is called *planning and preparation*, includes measures that must be taken before the gathering of data is initiated. This step includes, for example, formulation of research objectives, design of the study, development of study procedures and formulation of an ethics application. Step 2, which is called *execution*, includes activities for gathering of empirical data, such as making observations or performing interviews. When data have been gathered they are analysed and relevant conclusions are drawn in Step 3, which is called *analysis*. The analysis includes activities for examining the data in relation to the research objectives, such as performing significance tests or conducting content analysis of interviews.

Table 1.1 The degree of responsibility and work effort of the author for the different steps of Papers I, II, III and IV.

Step	**Degree of responsibility and work effort**			
	Paper I	Paper II	Paper III	Paper IV
1. Planning and preparation	medium	medium	medium	major
2. Execution	medium	medium	medium	major
3. Analysis	major	major	major	major
4. Preparation of paper	major	major	major	major
5. Presentation at conference	major	major	n/a	major

Step 4, which is called *preparation of paper*, includes writing up and submitting the paper, as well as addressing comments that are raised by the reviewers. Step 5, which is called *presentation at conference*, is only relevant for three papers of the present thesis (Paper I, II and IV). The step includes activities that are related to presentation of the paper at a scientific conference. Paper I, II and IV have all been presented at conferences by the author of the present thesis.

1.4.2 Related publications

Apart from the four thesis papers presented above, the author has also contributed to additional publications that are relevant for the study of flashing lights at emergency exits. Much of the research covered in related papers and reports is transferable to the problems that are studied in the present research. These related publications, which are also referenced in the thesis, are:

Nilsson, D., & Frantzich, H. (in press). Design of voice alarms – The benefit of mentioning fire and the use of a synthetic voice. *Pedestrian and Evacuation Dynamics 2008*, Wuppertal, Germany.

Nilsson, D., & Johansson, A. (2009). Social influence during the initial phase of a fire evacuation – Analysis of evacuation experiments in a cinema theatre. *Fire Safety Journal*, *44*(1), 71-79.

Nilsson, D. (2006). *En modell av det inledande utrymningsförloppet* [A model of the pre-movement phase] (No. 3138). Lund: Brandteknik, Lunds tekniska högskola.

2 Methods

The solution of a scientific problem requires the proper research strategy, i.e., a combination of research methods and data collection techniques. When choosing a strategy it is imperative to consider the objectives, since they determine what methods and techniques are suitable. A poorly considered strategy can jeopardise the quality of the research and lead to low validity and reliability of the results. It is hence essential to carefully consider both the choice of research method and the data collection technique before a study is initiated. The present chapter therefore focuses on methodological aspects and concludes with a description of the strategy that was used in the research.

2.1 Quality of research – reliability and validity

The quality of research is often expressed in terms of the reliability and validity of the results. Reliability refers to the repeatability of a study, i.e., the ability to get similar results if a study is repeated. There are several aspects that need to be considered in relation to reliability. Firstly, the study must be properly documented in order to ensure that it can be repeated. This means that the conditions, such as the participants and the setting, must be characterised and described in sufficient detail. Without this information a study can never be replicated, since it will not be possible to recreate the same conditions. Hence, proper documentation is an essential requirement that must be met before the reliability of the results can be discussed.

Secondly, reliability requires that the data collection techniques, e.g., questionnaires, interviews and observations, are able to give consistent results. For example, a written psychological test, which is a form of questionnaire, should result in the same (or similar) score if a person is retested with the same or an equivalent test (Anastasi & Urbina, 1997). If the scores from two separate test occasions differ significantly, the reliability of the results can be questioned. Much of the discussion about reliability can therefore be focused on the data collection techniques, i.e., on the precision of the measuring instruments of the study.

Validity refers to the correctness of the study findings, i.e., the extent to which the study measures what it is supposed to measure. Many different types of validity have been proposed (Anastasi & Urbina, 1997; Christensen, 2007; Yin, 2003), but internal and external validity are often identified as the two most fundamental types. Internal validity refers to the extent to which cause and effect relationships can be accurately identified (Christensen, 2007). If the internal validity of the results is high, it can be expected that the effects of the independent variables, e.g., an active evacuation system, on the dependent

variable, e.g., exit choice, has been properly established. This, however, does not necessarily mean that the findings can be generalised to a real-life setting, but merely that the cause and effect relationships of the study have been correctly identified.

External validity refers to the domain, e.g., people, settings or times, to which the findings can be generalised (Christensen, 2007; Yin, 2003). It is often useful to examine external validity in relation to the aims and objectives of a particular study. For example, if a study aims to explore the effectiveness of different fire alarms, the external validity of pre-announced experiments would be lower than that of unannounced experiments. The participants are not aware that they are taking part in an experiment if it is unannounced, which leads them to behave as they would have done in a real emergency. Since the main focus of research is to understand real-life phenomena and not just the research study, it is important to adequately consider to what domain the findings can be generalised.

It is an essential part of the research process to carefully examine quality aspects, i.e., the reliability and validity. In some cases, it is possible to measure quality quantitatively by using, for example, the standard reliability tests that have been developed for psychological tests (Anastasi & Urbina, 1997). In other cases, it is impossible to measure exactly how reliable or valid the results of a study really are. However, it is imperative to always consider reliability and validity aspects, since they will determine the combination of methods and data collection techniques that are most appropriate for addressing the objectives.

2.2 Research methods

The choice of an appropriate method is an important step towards solving a research problem. There are many different methods and some of the most common are experiments, case studies, surveys and archival analysis (Yin, 2003). As has been pointed out by Yin (2003), not all approaches are suitable for a specific problem. Yin argues that the type of question that the research seeks to answer dictates the choice of method. For example, experiments and case studies are often able to answer *how* and *why* questions. These types of questions are difficult to address with surveys and archival analysis, which are more suitable for exploring issues such as *who*, *what*, *where*, *how much* and *how many*.

Since the present research seeks to answer *how* and *why* flashing lights at emergency exits influence human behaviour in the event of fire, case studies and experiments are considered particularly relevant. The following sections briefly describe case studies and experiments and give some examples of

previous studies of human behaviour in the event of fire where the two methods have been used.

2.2.1 Case studies

Fire accidents can provide detailed information about human behaviour in the event of fire, but accidents need to be studied systematically to yield valuable data. One method that is suitable for studying fire accidents is the case study approach, which is described by for example George and Bennet (2005), and Yin (2003). Yin (2003) emphasises that a case study is an empirical inquiry that examines contemporary phenomena. In addition, these phenomena are studied in their real-life context, i.e., in the setting where they naturally occur. The context is hence not artificial or modified by the researcher, as is often the case for experiments.

Official investigations of fire accidents are common examples of case studies that can provide valuable information about human behaviour in the event of fire. Examples include the Göteborg nightclub fire inquiry (Statens haverikommission, 2001) and the Mont Blanc tunnel fire inquiry (Duffé & Marec, 1999). Investigations of fire accidents often rely on multiple sources of evidence, such as interviews, observations and computer simulations, in order to accurately determine the chain of events. The importance of many sources of evidence for case studies has also been pointed out by Yin (2003), who argues that data need to converge in a triangulating fashion in order to insure the validity of the results.

Most official investigations of fire accidents are mainly descriptive in nature, i.e., they focus on determining the chain of events before, during and after a fire. Case studies of fire accidents can also be explanatory and one example of this is the study of the Summerland fire that was performed by Sime (1985). Sime investigated the tendency of people to move towards familiar exits in a fire entrapment setting using transcriptions of witness statements as the main source of data. The data collection was influenced by the affiliative model, which predicts that people will move towards familiar persons and places in emergencies. A clear theoretical framework, e.g., the affiliative model, is imperative for case studies because it guides the collection and analysis of data (Yin, 2003).

The previous examples of case studies have all been single-case designs. It is also possible to include many fire accidents according to a multiple-case design (Yin, 2003) and one example of this is the study by Canter, Breaux and Sime (1980). Canter et. al. interviewed people who had been involved in fire incidents. The interviews focused mainly on behaviour and perception during the event. Based on an analysis of the data from the various cases a general

model of human behaviour in the event of fire was developed. The study by Canter et. al. is an excellent example of a multiple-case design that uses data from different cases to draw general conclusions about the studied phenomenon.

2.2.2 Experiments

The term experiment has been used to describe a range of different research methods. A distinction is often made between experiments that are performed in a controlled laboratory environment, i.e., laboratory experiments, and a real-life setting, i.e., field experiments (Christensen, 2007). In spite of dissimilarities that exist between different types of experiments, they share many characteristic features. One such feature is that they are all observations of phenomena (Christensen, 2007). In addition, the studied phenomena are produced by exposing participants to a situation that is controlled by the researcher. The degree of control may vary significantly depending on the exact nature of the experiment. For example, there are many factors that the researcher is not able to manipulate in field experiments. Some of these factors can be removed in laboratory experiments, since the researcher has more control over the experimental conditions.

As has been mentioned, experiments are observations of phenomena. The type of phenomenon that is observed can vary considerably, but a common requirement is that it should be something that is possible to record. Examples include actions, statements and answers to questions. The researcher is sometimes interested in an internal process that is not possible to observe directly. One example is how flashing lights at emergency exits are perceived. In this case, an observable behaviour is studied and the researcher uses the observation to infer something about the internal process (Christensen, 2007). For example, perception of flashing lights at emergency exits could be inferred from answers to questions about how participants interpreted the system.

Many experiments that have focused on human behaviour in the event of fire have involved actual evacuation behaviour in physical settings. Examples include unannounced evacuation experiments in the field (Frantzich, 2001a; Shields & Boyce, 2000) and controlled laboratory experiments (Heskestad, 1999; Jin & Yamada, 1994). However, an alternative approach is to introduce participants to a hypothetical scenario and ask them to predict how they would have behaved or perceived the situation. For example, the researcher could describe a fire scenario to participants and ask them to estimate how they would have acted in that particular situation. In the present thesis, a distinction is made between experiments where participants act based on a real physical setting and experiments where participants predict their behaviour or

perception of the situation based on a hypothetical scenario. The latter is called hypothetical scenario experiments and the former is divided into laboratory and field experiments.

Hypothetical scenario experiments

In hypothetical scenario experiments, participants make predictions about phenomena, e.g., their behaviour in a fire emergency, based on a hypothetical scenario. It is therefore not possible to observe evacuation behaviour directly, but instead this has to be inferred from the participants' predictions. The external validity of the results is therefore highly dependent on people's ability to accurately predict the studied phenomenon. Presentation of the scenario and available response options are also critical, since the experiment can compromise results if the scenario is presented inadequately or if the options are irrelevant.

Hypothetical scenario experiments have been used by Saunders (2001) in a study of decision making in office building fire evacuations. Participants viewed a video film and estimated their response to different fire cues in Saunders' study. Three cues were presented in the film, which was paused after each cue to allow participants to choose an action from a list of options. The list was based on previous research and was refined in several pilot studies to ensure that it only contained actions that were cognitively possible for the participants. The film was based on real office building fires and was reviewed by fire experts to ensure that it was realistic and representative. Saunders thus took steps to ensure that both the presentation of the hypothetical scenario and the response options were pertinent for office building fire evacuations.

The external validity of hypothetical scenario experiments relies on the ability of people to accurately predict the studied phenomenon. In some cases, it can be difficult for participants to estimate, for example, their behaviour based on an artificial scenario because they are not able to take surrounding factors into account. One example of such a factor is the influence that others have on the individual, i.e., social influence. Latané and Darley (1970) argue that people may not be fully aware of the importance of social influence on their behaviour in emergencies. Experiments that were performed by Latané and Darley revealed that others did influence people's response, but that participants were either unaware of the effect or unwilling to admit it. This suggests that people who are asked to predict their behaviour based on a hypothetical fire scenario may not always make an accurate prediction.

Laboratory experiments

A characteristic feature of a laboratory experiment is that it is performed in a controlled environment that the participants do not encounter during everyday routines (Christensen, 2007). Because the environment is not part of the participants' everyday activities, they have to be recruited for the experiment. This means that the participants are most often aware that they are taking part in a study. In some cases, however, laboratory experiments involve deception, i.e., misinformation about the purpose of the study. One example of this is the experiment by Latané and Darley (1970) in which participants were told that they were going to take part in a study about urban life. The true purpose of the experiment was to explore social influence on behaviour in fire emergencies, but this was not revealed to the participants since it would have influenced their response. Instead, the uninformed participants were subjected to a fire scenario, namely artificial smoke through a vent, while they were filling out a questionnaire. Although deception may lead to more realistic behaviour, it cannot be ruled out that the mere knowledge that one is taking part in a study can influence the external validity of the results. For example, it is possible that the participants in Latané and Darley's study were suspicious, which could very well have influenced their response.

The participants in laboratory experiments are often college or university students, since they are easy for the researcher to recruit. The use of students as subjects is sometimes questioned because they are not a random sample (Myers, 2002), which means that the results may lack external validity. However, the importance of the choice of population for the experimental results depends on the type of phenomenon that is being studied. There is, for example, reason to believe that there are differences between the risk perception of students and many other members of the public, since risk perception has been shown to correlate with education level (Sjöberg & Ogander, 1994). This suggests that laboratory experiments with students that aim to explore perception of risk may not necessarily produce results that can be extrapolated to other populations. More fundamental phenomena are less likely to be dependent on individual characteristics. For example, it seems reasonable that associations with the colour green are similar for students and other members of the public. However, associations with colours may vary between cultural settings, e.g., different countries.

Because of the question of external validity a number of previous studies have aimed to explore whether it is possible to reproduce results from laboratory experiments in real world settings, see for example Gigerenzer (1984). Based on these types of studies it is difficult to draw general conclusion about the external validity, since this depends on the exact nature of the experiment. In

many cases, however, it can be expected that trends identified in the laboratory are indeed relevant for real situations in spite of the artificial environment or the unrepresentative participant population. One reason for this is that participants are influenced by the situation, which was vividly demonstrated by the Stanford prison experiment (Zimbardo, 2008). Participants were given the role of either guard or prisoner in the experiment, which influenced their behaviour significantly. The guards often became cruel and the prisoners accepted humiliating treatment in spite of the fact that they were fully aware that they were only taking part in an experiment. Although the Stanford prison experiment is an extreme case, it clearly shows that participants are influenced by the situation. This suggests that a realistic environment can improve the external validity of the results compared to an artificial one.

One of the main benefits of laboratory experiments is that the researcher has a great deal of control over the experimental conditions. It is therefore possible to effectively isolate an aspect of interest by eliminating many confounding variables that would have been present in field experiments, e.g., ambient noise or other people. The high degree of control means that cause and effect relationships can often be identified, resulting in a high internal validity.

Laboratory experiments have been used to explore human behaviour in the event of fire in many previous studies. One example is the experiments by Jin and Yamada (1994), in which the effectiveness of an active evacuation system was evaluated in a smoke-filled environment. The tested system consisted of green lights at floor level that flashed in sequence to indicate an appropriate escape direction. In their study, Jin and Yamada asked the participants to give their estimate of the effectiveness of the system according to a seven-step rating scale. Furthermore, they implicitly assumed that the ability of the system to direct people through smoke, i.e., its effectiveness, could be inferred from the estimates given by the participants. Although these types of inferences can be criticized, they are often necessary in laboratory experiments. Another example is the study by Heskestad (1999) where the movement speed and the probability of making the right route choice were used to evaluate the effectiveness of different wayguidance systems.

Field experiments

As has been pointed out by Harrison and List (2004), it can sometimes be difficult to determine if a specific experiment should be categorised as a laboratory or a field experiment. For example, an evacuation experiment in a real tunnel with participants who have been recruited and properly informed about the study is undoubtedly performed in a realistic field environment. On the other hand, the tunnel might not be a part of the everyday routines of the

participants, which has been pointed out as a characteristic feature of laboratory experiments (Christensen, 2007). Harrison and List (2004) argue that there are many aspects that need to be considered when a definition of field experiments is made, e.g., the nature of the participant pool, rules, stakes and experimental environment. According to the terminology proposed by Harrison and List a common characteristic of field experiments is that a non-standard participant pool is used, e.g., not a student population. Furthermore, they divide field experiments into three categories, namely artefactual, framed and natural, depending on their field context.

Although it is recognised that it can be difficult to draw the line between laboratory and field experiments, it is believed that Harrison and List's proposed terminology, which was originally developed for the field of economics, is not entirely suitable for experiments that explore human behaviour in the event of fire. Harrison and List, however, make a valid point when they suggest that the distinction between different types of experiments should ideally be based on many aspects.

In the present thesis, field experiments are defined as experiments that are performed in a field environment, e.g., a real building or tunnel, that the participants encounter or could encounter during everyday routines. This means that an evacuation experiment that is performed in an office building with participants who are unrepresentative for the setting, e.g., students instead of office workers, is not a field experiment. The office building can, in this case, be seen as a controlled laboratory environment. If the participants instead are representative for the setting, e.g., office workers in an office building, the experiment is a field experiment according to the proposed definition.

One of the main benefits of field experiments is that the external validity is high because they are performed in a real world environment with representative participants. In addition, field experiment can be unannounced, i.e., participants are not given information about the study beforehand. One example of this is the unannounced evacuation experiments in a cinema theatre by Bayer and Rejnö (1999). It can be expected that the external validity of the results from the cinema theatre experiments, e.g., the pre-movement time and movement patterns, is high, since participants were not informed about the evacuation beforehand. From the viewpoint of the participants the evacuation could very well have been a result of a real fire. It is therefore reasonable to suspect that people acted as they would have done in a real emergency.

It is often difficult for the researcher to control the conditions involved in field experiments. This means that an aspect of interest cannot be easily isolated by eliminating various confounding variables. The presence of many confounding

variables makes it hard to determine cause and effect relationships within the experiment, which is a threat to the internal validity of the results.

Field experiment have been used frequently in the past to study human behaviour in the event of fire, see for example Frantzich (2001a), Kimura and Sime (1994), Proulx and Sime (1991), and Shields and Boyce (2000). These types of experiments have provided valuable information about people's response to active evacuation systems, mainly fire alarms. Field experiments are seldom repeated because they are expensive and difficult to set up. One exception is the study by Bayer and Rejnö (1999) where eighteen experiments were performed with different participants in the same cinema theatre, namely three experiments for each of the six fire alarms that were tested. However, such a rich data set is often difficult to achieve with field experiments.

2.3 Data collection techniques

The data collection techniques are the measuring instruments of the study. Three techniques that are often mentioned and that are considered particularly important for the present research are questionnaires, interviews and observations. These instruments can be used individually, but they are preferably combined to improve the quality of the research.

2.3.1 Questionnaires

A questionnaire, which in this thesis is defined as a set of written questions that the respondent answers in writing, is often a cost-effective and practical measuring instrument. One of the benefits is the strict format and hence consistency of written questions, which means that all respondents are given the same type of information. However, the format is also associated with limitations. For example, questionnaires offer limited possibilities to ask probing questions or to get clarifications as compared to interviews.

One debate that is often brought up in relation to questionnaires is that of open versus closed questions (Foddy, 1993; Oppenheim, 1992; Schuman & Presser, 1979). An open question requires that the respondents write their own answer, whereas a closed question provides them with response options. One common assumption is that open questions allow people to state what is on their mind without being influenced by suggestions from the researcher (Foddy, 1993). In an ideal case, the answers should therefore reflect what is important to the respondents. However, it has been argued that there are factors that inhibit people from mentioning the most relevant matters. For example, respondents may not mention things that they feel are obvious or threatening (Foddy, 1993).

All replies must be classified, i.e., coded, in order to enable analysis of answers to open questions. Coding is often a time consuming process that requires adequate training (Oppenheim, 1992). There is always a risk that data are lost or misrepresented if the coding frame, i.e., the model for classifying the data, is inappropriate. In this regard the closed questions are easier to analyse because the coding is already determined by the response options.

One point that is often made in relation to closed questions is that the response options are very much a part of the question itself (Foddy, 1993; Oppenheim, 1992). The options inform the respondents about the purpose, i.e., the types of answers that are expected. A closed question can therefore become a selection between the set of provided replies, which means that important answers might be missed. It is therefore important to provide a list of options that includes all relevant alternatives, e.g., all types of behaviour that can be expected in a specific situation. It has also been suggested that response options may have a positive effect because they work as memory cues that make respondents remember answers that they would otherwise have forgotten (Foddy, 1993).

There appears to be both advantages and disadvantages associated with the two types of questions, but they may also complement each other in many areas. It is therefore often recommended that open and closed questions are combined in different phases of the research (Schuman & Presser, 1979).

Reliability of data is an important aspect of a questionnaire since such questionnaires are the measuring instruments of the study. As has been mentioned, it is sometimes possible to measure the reliability directly, e.g., with the standard reliability tests that have been developed for psychological tests (Anastasi & Urbina, 1997). However, many tests require that the questionnaire focus on a phenomenon that is not highly situation-specific. For example, IQ can be seen as an individual characteristic whereas human perception of an emergency is highly dependent on the setting. Since it is difficult to recreate the exact conditions of an emergency, it can be extremely hard to evaluate the reliability of questionnaire data about the perception of such an event. A person's IQ, on the other hand, can be measured many times without requiring considerable attention to such things as the physical setting.

One of the most important measures for improving reliability is to ensure that the questionnaire is interpreted similarly by all the respondents. If the questions are interpreted differently by respondents, it is probable that the answers will vary significantly. This implies that the reliability of the results would be low. One recommendation is therefore to clearly tell the respondents about the purpose, so that they take the same information into account when they give their answers (Foddy, 1993). Several studies have also shown that

aspects such as wording, ordering and context influence how questions are perceived (Foddy, 1993). Since it is difficult to estimate the effect of all potential factors, it is often appropriate to perform pilot work before a method is finalised (Oppenheim, 1992). Pilot work can reveal if the questions are interpreted correctly and can be used to improve the original questionnaire. Editing rules, which are well-founded principles for formulation of questions, can also be used to improve the quality of questionnaires, see for example Foddy (1993).

2.3.2 Interviews

Interviews share many similarities with questionnaires, but they involve oral instead of written communication. This means that the interpersonal skills of the researcher become important and that there is always an apparent risk of introducing interviewer bias. Interviews can be performed with either single individuals or groups of people and may involve different degrees of structure. For example, a standardised interview often consists of a set of pre-defined questions, whereas a depth interview has a much more lenient format with topics rather than precisely formulated questions (Oppenheim, 1992).

The fact that interviews involves questions to respondents means that many of the issues that have been discussed in relation to questionnaires are also relevant for interviews, see Section 2.3.1. For example, the debate over open versus closed questions is applicable, although it can be expected that open questions are more common than closed question in most interviews. Editing rules and pilot work are also important for interviews to ensure that the questions are interpreted as intended, i.e., as a way of improving reliability.

One advantage of interviews over questionnaires is that the interviewer can ask probing questions in order to clarify or explore a response. Probes should be non-directive, so that that the answers are not influenced. Standard probes are sometimes suggested as a way of minimising interviewer bias (Fowler & Mangione, 1990). However, it has been pointed out that even very standardised probes can be directive and may influence the outcome of an interview if they are used inappropriately (Foddy, 1993). Another important aspect of interviews is that they can be combined with observations of behaviour (Anastasi & Urbina, 1997). For example, it can be observed how the respondents behave, e.g., change their voice, in relation to specific questions.

2.3.3 Observation

Questionnaires and interviews are sometimes criticized because they rely heavily on information from respondents. Respondents may not be able to give valid answers to a specific question. As mentioned previously, Latané and

Darley (1970) found that participants in fire evacuation experiments were either unaware, or unwilling to admit, that others had influenced their responses. Observations, on the other hand, clearly showed that social influence was important. Latané and Darley (1970) therefore argue that observation is the only way to study human behaviour in emergencies.

One situation where observations may be better that questionnaires and interviews is unannounced evacuation experiments. In these types of experiments, the participants are initially not aware that they are taking part in a study. This means that they may potentially believe that it is a real emergency. When the experiment is terminated the participants are told about the deception, i.e., that they were only taking part in an experiment. This information may lead to cognitive dissonance, i.e., a conflict between the original belief that it was a real emergency and the new belief that it was only an experiment. This type of conflict results in pressures to reduce or eliminate the cognitive dissonance (Festinger, 1957). One possible way for the participants to reduce dissonance is to modify their beliefs about how they perceived the situation. If this is the case, questionnaires and interviews are not suitable instruments for measuring how participants interpreted the emergency. Instead, it may be preferable to observe their behaviour and infer from the observations how the situation was perceived.

All observation involves some degree of judgement, which means that it is not an instrument that is free from error. There is always a risk that the observer influences the outcomes due to such factors as expectations or ability. Observations by different people may therefore give different results, which is a threat to reliability. One way to reduce the observer influence is to use well-defined procedures, i.e., techniques for making observations. Examples include running records, time sampling, checklists and rating scales (Irving & Tennent, 1998). All these procedures attempt to standardise the way an observation is performed and documented.

Observations can also benefit from a clear operational definition of the studied phenomenon. For example, a study of recognition and pre-movement time in cinema theatre evacuations requires that the associated behaviour types are clearly defined, see Nilsson and Johansson (2009). In the cinema theatre example, a lack of clear definitions would have led to low reliability. Observations can also be improved if they are filmed, since this make it possible to study the material as many times as necessary (Gillham, 2008). The researcher can perform multiple checks of the observations, which means that the reliability can often be improved.

2.3.4 Multiple sources of evidence

Data collection techniques are associated with both advantages and disadvantages, but different techniques can often complement each other. Multiple measuring instruments can therefore be used together to improve the quality of the research. Yin (2003) argues that the accuracy of case study findings can be improved if they are based on multiple sources of evidence, i.e., techniques. Improved accuracy implies enhanced reliability of the findings. The benefit of using multiple techniques is not exclusive for case studies and a similar trend can be expected for other types of research methods, e.g., experiments.

Yin (2003) also points out that multiple sources should be used in a triangulating fashion. This means that data from different instruments are used together to corroborate findings about the studied phenomenon. Triangulation can lead to improved validity because multiple measures of the same phenomenon are used (Yin, 2003). For example, if both self-reported (questionnaire) and observed accounts (observations) support that one particular behaviour occurred in an experiment, it seems more likely that this was actually the case than if the behaviour was only supported by one source. The quality of research can therefore benefit from the use of multiple data collection techniques and data triangulation.

2.4 Selection of research strategy

Previous sections of this chapter have described different research methods that have been used to study human behaviours in the event of fire, see Section 2.2. All these methods are associated with both advantages and disadvantages that need to be considered in relation to the research objectives. Not all methods are suitable for a given research problem, and there is no universally applicable approach. Similarly, there is no universal data collection technique that will always produce the most reliable measurements. Careful selection of a research strategy, i.e., a combination of research methods and data collection techniques, is therefore essential in order to ensure both high validity and reliability of the results.

For the present research, the selection of an appropriate strategy is mainly dictated by the first objective, which is to develop recommendations that describe how flashing lights at emergency exits should be designed in buildings and road tunnels. These recommendations should be based on research that aims to explore the use of flashing lights by investigating how the system is perceived and how it influences human behaviour. This means that the chosen strategy must provide an accurate account of both human behaviour and perception in relation to the studied system. Furthermore, it must produce

results with high external validity, i.e., results that are applicable to real fire emergencies in both buildings and road tunnels. The system must therefore be adequately tested to ensure that it functions as intended.

According to the objectives, the research on which the recommendations are based should also explore important design aspects of flashing lights at emergency exits. This means that the chosen strategy must be able to identify aspects that are important for the performance of the system and provide solutions to any design problems that are discovered.

The first step towards the development of a research strategy is to determine what methods are suitable. Case studies have been used successfully in the past to study human behaviour in fire emergencies, but the method is not considered appropriate for exploring the use of flashing lights at emergency exits. The main reason for this is that the studied system is a relatively new active evacuation system and is still uncommon in most buildings and road tunnels. In addition, fire is a relatively uncommon occurrence. This suggests that it would be difficult to find relevant cases and that the available data would therefore be very limited. Another disadvantage of the case study approach is that it is difficult to control exactly what design aspects to focus on. It would therefore be virtually impossible to investigate the importance of an isolated feature, e.g., the colour of the lights, because of differences between cases.

Experiments are regarded as the most appropriate method for the present research, since they give the researcher control over the experimental conditions. This means that the environment can be modified to include flashing lights at emergency exits even if this is an uncommon system in most buildings and road tunnels. The three different types of experiments are, however, associated with limitations that need to be considered in relation to the objectives that were mentioned earlier in this section.

Hypothetical scenario experiments can potentially provide very useful data about flashing lights at emergency exits. One of the main benefits of the approach is that it is easy to set up an experiment and that it is possible to include many participants. The researcher also has a great deal of control, which suggests high internal validity of the results.

One important limitation of hypothetical scenario experiments is that people are not always able to accurately predict how they would behave in a real situation because they are unable to take surrounding factors into account, see Section 2.2.2. This inability is likely more prominent for unfamiliar scenarios, e.g., scenarios that involve estimation of behaviour in relation to a new active evacuation system. It is believed, however, that people are better able to

estimate their initial perception of a new system, since this perception is influenced less by other factors than their behaviour. It is also estimated that the external validity is further improved if a comparative approach is applied, i.e., if people's estimation of their perception is only used to rank different designs. For example, if it is shown that bright lights are perceived as more directive than dim lights, i.e., a relative value, it seems reasonable that the same relation would hold for real fire emergencies. However, an estimation of the bright lights as sufficiently directive, i.e., an absolute value, would most likely not be valid for real fire emergencies.

Many previous studies have successfully used laboratory experiments to evaluate evacuation systems (Heskestad, 1999; Jin & Yamada, 1994). This approach is also deemed appropriate for the study of flashing lights at emergency exits, but it is associated with some important limitations that must be considered. As mentioned previously, laboratory experiments give the researcher a great deal of control, which means that the approach can be useful for exploring specific design aspects of the studied system. The high degree of control also implies that the internal validity is high, but the artificial nature of the experiment weakens the external validity of the results. For example, participants in laboratory experiments are often aware that they are taking part in a study, which probably influences their response. There may also be many surrounding factors that influence people's perception and behaviour in the event of fire, but many of these factors can often be removed in a laboratory experiment in order to isolate an aspect of interest.

As was the case for the hypothetical scenario experiments, laboratory experiments are appropriate for comparing different designs. If an experiment reveals that people prefer one design over another, it is likely that the same relation also holds in the event of fire. It may, however, be difficult to determine exactly how effective a specific design will be in a real emergency. Thus, one of the main benefits of laboratory experiments is that they can reveal general trends about the studied systems. The approach can therefore be particularly useful for discovering potential problems associated with a specific design and for identifying performance differences between designs. However, laboratory experiments should be combined with other research methods to reveal how the system performs in real-life situations.

The study of flashing lights at emergency exits requires the use of field experiments to ensure the external validity of the findings. It would be virtually impossible to determine how the system is perceived and how it influences human behaviour in real fire emergencies without using field experiments. Since field experiments are performed in real-life environments, it is possible to carry out unannounced evacuations, which can be expected to be very

similar to real fire emergences from the viewpoint of the participants. It is therefore reasonable that unannounced field experiments will provide results with high external validity.

One common argument against field experiments is that the researcher does not have control over conditions, which poses a treat to the internal validity. The cause and effect relationships can hence be difficult to determine because of many confounding variables that cannot be eliminated. Another disadvantage is that field experiments are expensive and difficult to set up. For practical reasons, it is therefore not feasible to perform vast numbers of experiments to explore different design aspects of the studied system. These limitations mean that, although field experiments are necessary, they should not be the only research strategy used to study flashing lights at emergency exits.

The above discussion clearly shows that the three types of experiments are associated with different strengths and weaknesses in relation to the study of flashing lights at emergency exits. It is also clear that the types of experiments complement each other, which suggests that they should be combined in order to provide an effective research strategy. The present research therefore combines hypothetical scenario experiments, laboratory experiments and field experiments in three separate steps, see Figure 2.1. These three steps, which correspond to the papers, and their associated research methods are:

1) Identify problem – laboratory experiments (Paper I)
2) Solve problem – laboratory experiments and hypothetical scenario experiments (Paper II)
3) Test system – field experiments (Paper III and IV)

Step 1 (identify problem) focused on finding a system with flashing lights that could potentially influence exit choice in fire emergencies. Furthermore, important design problems of the system were identified. These problems were then studied in Step 2 (solve problem) in order to find an appropriate design solution. Finally, the refined system was tested in the field, i.e., two buildings and a road tunnel, in Step 3 (test system). This was performed to check if the refined system, which was a result of Step 1 and 2, was able to influence people's choice of exit.

2.4.1 Identify problem – Paper I

A laboratory experiment was performed in a smoke-filled tunnel in Step 1 (Paper I). One of the aims of the experiment was to evaluate two different systems with flashing lights at emergency exits, namely orange flashing lights next to the emergency exit sign and rows of sequentially flashing lights on each

side of the exit, see Figure 2 in Paper I. The design of both systems was based on previous research and wayguidance systems in other applications. The row of sequentially flashing lights was based mainly on research by Jin and Yamada (1994) about way-finding through smoke. Research on flashing blue lights at emergency exit signs (McClintock et al., 2001) aided the design of the other system, but orange instead of blue lights were used since it was believed that orange would be more clearly visible through smoke.

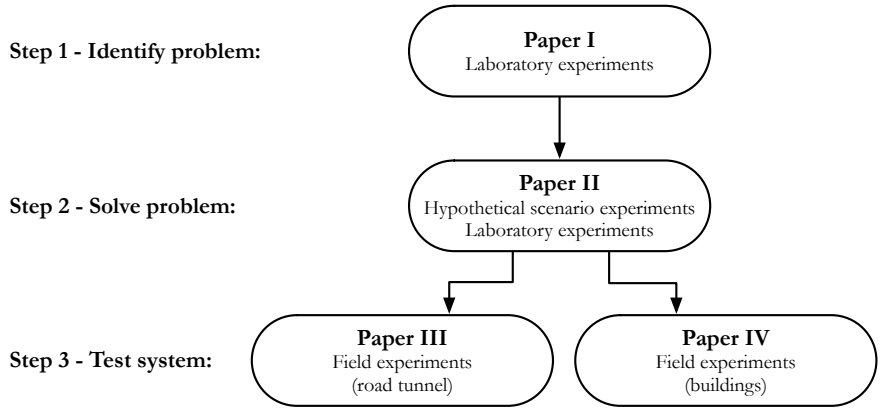

Figure 2.1 The research strategy.

A laboratory experiment was chosen in Step 1 because it gives the researcher a great deal of control and because it can reveal general trends about the studied systems, e.g., discover potential problems. The conditions of the experiment were controlled by eliminating many of the confounding variables that would have been present in a real fire emergency. For example, participants took part one at a time to avoid social influence and limited extra information was used in the tunnel, e.g., no alarm or additional wayguidance systems.

In order to improve the external validity of the results, the experiment was designed to be as similar as possible to a real fire emergency in a road tunnel. Previous experiments, such as the Stanford prison experiments described in Section 2.2.2, have shown that people can be strongly influenced by the setting, which suggests that a realistic environment will provide results with higher external validity than unrealistic ones. The experiment was therefore designed to be similar to a real fire emergency by creating an environment with cars and eye-irritating smoke. A short film of a drive into a road tunnel was also shown to participants before they entered the smoke-filled tunnel in order to convincingly introduce the tunnel fire scenario. Participants were also given safety instructions and general information about the experiment. Specific

information, e.g., descriptions of the tested systems, was not given because this would have influenced their behaviour.

Three data collection techniques, namely questionnaires, interviews and observations, were used in the laboratory experiment. Observation was made possible through the use of a thermal imaging camera that filmed participants through the dense smoke. The three techniques were, as far as possible, used in a triangulating fashion to improve the reliability of the results. One example is that data from both interviews and observations were used to draw conclusions about the type of information that was important to participants, e.g., the preference for tactile over visual information.

A number of measures were taken to improve the reliability of the results. The questionnaire, which was filled out by the participants after exiting the tunnel, contained questions that focused mainly on their behaviour and perception of the tunnel environment, see Frantzich and Nilsson (2003) for the entire questionnaire. Particular attention was placed on whether or not participants saw flashing lights and how they interpreted the system. Most of the questions were of the closed type and many were based on questions from previous evacuation experiments (Frantzich, 2000; Frantzich, 2001b). Parts of the questionnaire were, however, very specific for the experiment, which meant that some questions could not be based on previous experience. All questions were therefore discussed at length in the project group to ensure that the formulation followed appropriate editing rules and that the response options were relevant.

In addition to filling out a questionnaire, some participants were also interviewed. The interviewees watched a film from the thermal imaging camera of their walk through the smoke-filled tunnel and were asked to explain their behaviour and thoughts. Limited questions were asked by the interviewer in order not to influence participants' responses. Non-directive probing questions were used, however, to explore the meaning of unclear statements or explanations. The films were also analysed. Since films were used, the material could be studied multiple times to improve the reliability of the observations. The observations focused mainly on route choice, which was determined according to a well-defined procedure that combined the films and measurements in CAD drawings. The films were also analysed to get a qualitative description of way-finding behaviour, e.g., hesitation and the use of tactile information.

Based on the outcomes of the laboratory experiment in Step 1, it was decided to continue with the system with flashing lights next to the emergency exit sign. This system was chosen because the results suggested that it had the greatest potential. However, the experiment also identified a potential design

problem. The orange lights seemed to be not sufficiently encouraging. Step 2 therefore focused on exploring different design aspects of flashing lights at emergency exits.

2.4.2 Solve problem - Paper II

Three experiments were performed in Step 2 (Paper II). One of the aims of the experiments was to compare different designs of the studied system, namely the type and colour of the flashing lights. Another aim was to explore if flashing lights at emergency exits could more effectively influence people's choice of exit than the standard design, i.e., only a back-lit emergency exit sign above the door. Since different design aspects were going to be compared, i.e., a comparative approach, hypothetical scenario experiments and laboratory experiments were combined. These two methods were considered appropriate because they give the researcher control over the conditions, which means that the aspects of interest can be isolated by eliminating many confounding variables. As mentioned previously, the comparative approach can potentially improve the validity of the results compared to an absolute approach for both hypothetical scenario experiments and laboratory experiments.

Two of the experiments in Step 2 were laboratory experiments that were performed in a sparsely furnished corridor at Lund University. The setting was chosen because it was a controlled environment, which meant that many confounding variables could be eliminated. For example, the participants took part one at a time in order to reduce the effect of social influence. The participants, namely newly arrived students who were not familiar with the building, were also given limited information about the exact nature of the experiment in order not to influence their behaviour. They were only instructed to imagine a fire scenario and to act accordingly. The participants were faced with a choice between two emergency exits in the first experiment, see Figure 1 in Paper II. Both the design of the exits, e.g., the colour and type of flashing lights next to the sign, and the start position were varied. In the second laboratory experiment, participants moved toward an emergency exit at the end of the corridor, but they could choose an alternative emergency exit midway, see Figure 4 in Paper II. The design of the alternative exit was varied in order to explore if green flashing lights could more effectively influence exit choice compared to the standard design, i.e., only a back-lit emergency exit sign above the exit.

The participants' exit choice was recorded by an observer and no video cameras were used in the two laboratory experiments. This procedure was selected because the task of determining people's exit choice was deemed to be uncomplicated. Participants were assumed to have made their choice when

they began to move decisively towards an exit. Repeated observations were hence not considered necessary to ensure the reliability of the results.

After the laboratory experiments, participants filled out a questionnaire that included questions about their associations with the tested systems, as well as with different colours in emergencies. All these questions were closed and considerable effort was therefore made to construct relevant response options. The options were partially based on the outcomes from the experiment in Step 1, which showed that people associated light in the smoke-filled tunnel both with something negative, e.g., threat or fire, and something positive, e.g., safety or exit (Frantzich & Nilsson, 2003). An equal number of positive and negative response options were provided to avoid unnecessary directive influence. The closed questions can therefore be seen as a selection between positive and negative associations. Furthermore, the stated associations were used to infer something about the usefulness of the system or colour in emergencies by assuming that a positive assumption is more preferable than a negative.

The third experiment of Step 2 was a hypothetical scenario experiment. In the experiment participants were shown a display of flashing lights with different colours. The participants were instructed to imagine that the lights were going to be used in combination with an emergency exit sign. They were then asked to grade the extent to which they associated the different lights with an emergency exit. The estimates given by participants were then used to infer something about the appropriateness of the tested lights by assuming that a high degree of association with emergency exits is more preferable than a low degree.

The results from the experiments suggest that green lights should be used in favour of lights of other colours. It was therefore decided to continue with research about green flashing lights next to the emergency exit sign in the third and final step. Although the experiments of Step 2 suggest that the tested system can potentially influence people's choice of exit in emergencies, the results are not conclusive. Both hypothetical scenario experiments and laboratory experiments raise questions about external validity, which implies that the system should be tested in field settings before it can be relied upon. The refined system was therefore tested under realistic conditions in Step 3.

2.4.3 Test system – Paper III and IV

Field experiments were performed in Step 3 to test the effectiveness of green flashing lights next to emergency exit signs. The experiments involved fire evacuation in both tunnel (Paper III) and building environments (Paper IV). None of the evacuations were announced, which meant that participants were

not given information about the evacuation or the tested system beforehand. This procedure was used to ensure high external validity of the results.

The tunnel evacuation experiment was performed with partially informed participants in a road tunnel, the Göta tunnel, in the city of Göteborg (Paper III). Due to ethical reasons, participants had to be recruited for the experiment, but they were given limited information about the exact nature of the experiment in order to create an element of surprise. The participants were only told that they were taking part in a study about driving behaviour and technical installations, and no mention was made of fire, emergency or evacuation during the recruitment and preparation process. Since all participants were from the Göteborg area, most of them used a tunnel at least once per week (Frantzich, Nilsson, Kecklund, Anderzén, & Petterson, 2007). This meant that the participants could potentially encounter the tunnel environment during everyday routines. They were hence representative for the chosen setting and the tunnel evacuation experiment can therefore be seen as a field experiment.

There were several aims associated with the tunnel evacuation experiment. The most important aim for the present thesis was to study people's perception of and response to green flashing lights at emergency exits in the tunnel environment. More specifically, the study focused on whether the lights could influence motorists to leave their vehicle and choose specific exits. The evacuation experiment also focused on the time to escape, general evacuation behaviour, emotional state during evacuation and fire alarms in road tunnels.

Multiple data collection techniques were used in a triangulating fashion in the tunnel evacuation experiments in order to improve the reliability of the results. Three techniques, namely questionnaires, interviews and observations, were utilized. The interviews were performed with both individual participants and groups. In the individual interviews, the participants followed the route that they had chosen in the evacuation, i.e., from the vehicle to the emergency exit, and were asked open questions at different locations. This procedure was used since it is believed that retracing of events has a positive influence on the recall of information, i.e., leads to higher reliability. In the group interviews the participants were also asked open questions about the evacuation. The participants were divided into three groups that were interviewed separately.

Answers from these three groups could therefore be compared in order to identify common trends and topics. All the participants also filled out a questionnaire with both closed and open questions. Since many of the questions in the interviews and questionnaire were very specific for the tunnel setting, they could not be based solely on previous experience. All the questions were therefore discussed by members of the project group to ensure

that the formulation followed appropriate editing rules and that relevant response options were used.

The building evacuation experiments were performed in two types of buildings, namely an office building and a cinema theatre (Paper IV). These two building types were chosen because they represent two fundamentally different settings. People in office buildings are typically familiar with the building since they spend considerable time there. This means that they, most likely, know where different exits lead. Cinema visitors, on the other hand, are less familiar with the building since they spend limited time there. They may therefore not know exactly where different exits lead, which can potentially be an influential factor during evacuation. The two different building types were therefore chosen to increase the external validity of the results.

Both the office building and cinema theatre experiments were designed as comparisons between independent groups of people. One of the groups was exposed to green flashing lights at emergency exits during evacuation while the other was not. For example, two experiments were performed with, and two without, flashing lights in the cinema theatre. The participants consisted of cinema visitors who attended the selected shows, and none of the participants took part in more than one experiment. In the office building, flashing lights were installed on selected floors. This meant that the behaviour and perception of participants exposed to green flashing lights could be compared to that of a control group who were not.

Two data collection techniques were used in the building evacuation experiments, namely questionnaires and observations. The questionnaires consisted of open questions and aimed to explore how the flashing lights were perceived. More specifically, the questions focused on important features of exits and were based on the Theory of Affordances, see Section 4.4. The open format was chosen to avoid influencing the participants' answers. Participants were only asked to point out features and no mention was made of any specific feature or system. In order to ensure that the questions were interpreted as intended, they were tested in a pilot study with students at Lund University.

All the experiments of Step 3 were filmed with video cameras in order to facilitate observation. The video films were studied multiple times to ensure high reliability. The type of behaviour that was studied, i.e., exit choice, was also clearly defined in operational terms before analysis. People were assumed to have chosen an exit if they walked out through that exit. This definition turned out to be clear and observation of exit choice was therefore straightforward. Attempts were also made to conceal the cameras as much as possible to avoid suspicion amongst participants. An analysis of the video films

showed that people did not look directly at the cameras, which suggest that they were not noticed.

The field experiments of Step 3 indicate that green flashing lights can be used to influence exit choice in fire emergencies. However, the results also show that there are problems associated with the tested system. For example, the system does not seem to be as effective in an office building as in a cinema theatre, which may be due to the occupants' level of familiarity with the building. The results of the field experiments hence suggest that there are additional aspects that can be investigated further according to an iterative process.

2.4.4 A proposed research strategy

The previous sections provide a detailed description of the research strategy, i.e., the combination of research methods and data collection techniques, that was used to explore flashing lights at emergency exits in the four papers. It is believed that the strategy is not only appropriate for the present research, but that it can also be used for future testing and evaluation of other evacuation systems. Figure 2.2 shows a proposed universal research strategy for the development of future systems. The strategy is divided into three steps, namely identify problem, solve problem and test system, according to the description in Section 2.4.

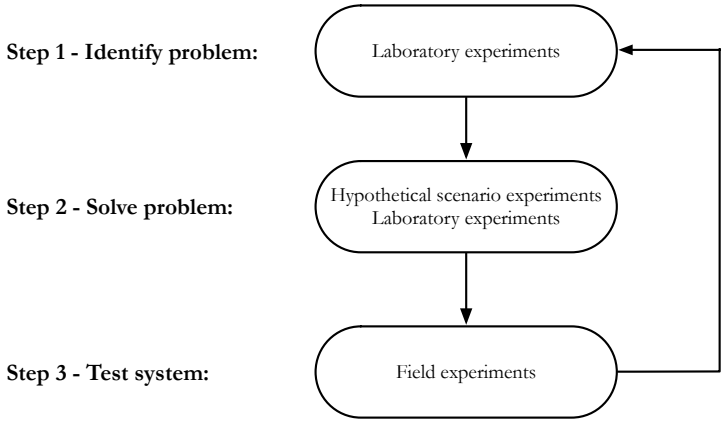

Figure 2.2 A proposed research strategy for developing evacuation systems.

In Step 1 of the research strategy (identify problem), laboratory experiments are performed with one or several evacuation systems in order to identify potential design problems. Laboratory experiments are considered most appropriate because they give the researcher a great deal of control over the experimental conditions. This means that an aspect of interest, such as the performance of evacuation systems, can be isolated and studied by eliminating many of the confounding variables present in field experiments. The laboratory experiments can thus reveal general trends about the tested systems, such as potential design problems.

Step 2 (solve problem) focuses on resolving the design problems that are identified in Step 1. It is considered appropriate to use a comparative approach. i.e., to perform experiments where different designs of a system are compared with each other. Both laboratory experiments and hypothetical scenario experiments are considered appropriate because they, as mentioned previously, give the researcher a great deal of control and hence make it possible to study a specific aspect, e.g., the importance of colour. Furthermore, it is believed that the two methods provide results with adequate external validity in most cases due to the comparative nature of the experiments. Step 2 can therefore reveal which of the tested system designs is most appropriate and should be tested in the subsequent step of the research.

In Step 3 (test system), the most appropriate design from Step 2 is tested under realistic conditions to ensure that it works as intended. It is appropriate to use field experiments, since the conditions must be realistic in order to ensure the external validity of the results. The experiments should preferably be unannounced to create a situation that is similar to a real fire emergency. They should also be performed in the type of environment where the system is intended to be installed to further improve external validity of the findings. Step 3 can hence reveal if the tested evacuation system works as intended.

In the present research, Step 1, 2 and 3 were performed in sequence and none of the steps were repeated. However, new potential design problems, i.e., problems that had not previously been considered, were revealed in Step 3. In order to more clearly identify these problems, new laboratory experiments could be performed, which corresponds to an iterative loop from Step 3 to Step 1, see Figure 2.2. By using this iterative process a system that is more effective than the green flashing lights of Step 3 might have been identified and developed. It is therefore recommended that the research strategy includes an iterative loop according to Figure 2.2. This is considered particularly important if major design problems are discovered in Step 3.

Various types of data collection techniques can be appropriate in the different steps of the research strategy. Questionnaires, interviews and observations are

often a good way to get data about human behaviour and perception, but there might be other techniques that are more appropriate in specific situations. The researcher should therefore carefully consider how data is collected and choose techniques that suit the experimental conditions. It is, however, considered important to use multiple sources of evidence in a triangulating fashion in each of the steps in order to improve the reliability of the findings.

The proposed research strategy relies heavily on experiments with human participants. Many experiments can also involve escape from a simulated fire. For these types of evacuation experiments, there is a risk of physical and psychological injury. It is also possible that the personal integrity and rights of the participants can be violated. It is therefore important to not only focus on methodological aspects, but also on relevant ethical issues.

3 Ethics

Experiments with human participants can be a rich source of data and, as was pointed out in the previous chapter, are an appropriate method for studies about evacuation systems. However these types of experiments are associated with ethical issues. Because humans are taking part, the researcher must consider and adequately deal with risks of injury and possible violations of integrity and rights. It is, however, not necessarily self-evident if an experiment is ethically viable or not. Although it may be generally accepted that participants should not be harmed during experiments, this does not necessarily mean that all experiments for which there is even a remote probability of injury should be avoided. Another common ethical rule is that participants should be informed about a study beforehand, so that they can decide if they want to take part, i.e., give informed consent. However, if the purpose of an experiment is to study the response of people, e.g., how people respond when they hear a fire alarm, this type of information may alter their behaviour and make the results meaningless. Unannounced experiments may thus be the only way to get valid results, but how should this violation of informed consent be handled to be ethically defensible?

There are many examples of experiments involving human participants that are commonly considered unethical. Among the most well known are the experiments that were performed in German concentration camps during the Second World War (Nuernberg Military Tribunals, 1949b). At Dachau concentration camp people were put in icy cold water for up to three hours in order to study hyperthermia. Numerous participants of the cold water immersion experiments suffered life-long injuries or death. The participants, who consisted of prisoners, were in many cases also forced to take part and were given limited information about the study. The experiments violated many basic human rights and led to the development of the Nuremberg Code (Nuernberg Military Tribunals, 1949a), which is a set of ten ethical rules for medical research.

It may be argued that the experiments performed during the Second World War were extreme and were a direct result of a totalitarian regime, but unethical experiments have also been performed in democratic societies. One example is the Tuskegee experiment, which was a study of the natural history of untreated syphilis (CDC, 2008; Jones, 1993). The study was initiated in 1932 and was abruptly terminated in 1972 when it caused headlines in the American media. The initial study population of the Tuskegee experiment consisted of 600 poor black men in Alabama. Approximately two thirds of the men had syphilis and the remainder were part of a healthy control group. During the forty year long study the participants with syphilis were given limited

information about their condition and were not offered appropriate treatment even though it was discovered in the nineteen forties that antibiotics was an effective cure. One of the main arguments against the Tuskegee experiment is that participants were misled and could therefore not make an enlightened decision about taking part in the experiments or seeking medical assistance elsewhere.

Most people would probably agree that both the Tuskegee experiment and the cold water immersion experiments of the Second World War are examples of unethical research, but there are many examples of studies that cannot easily be categorised as unethical. One example is the obedience experiment performed by Milgram (1963). The participants in Milgram's experiments believed that they were taking part in a study about learning and memory, but the real aim was to study people's tendency to follow orders. In the experiment, a teacher asked a learner questions and administer electric shocks with increasing voltage for every incorrect answer. The participants were always given the role of teacher and an actor played the learner. No electric shocks were actually delivered, but the participants were led to believe that they were administering shocks to the learner. In addition, the learner repeatedly said that he had a heart condition to ensure that participants were aware that the electric shocks would be dangerous. An experimenter in the room prompted the participant to continue in case he hesitated.

Milgram's study caused a debate about ethics and it was criticized by other researchers because they believed that the experiment was not ethically viable (Baumrind, 1964). The experiment was questioned because participants experienced great tension and because the study could possibly have led to after-effects. It was therefore argued that these types of potentially stressful experiments should require that participants are properly informed about possible dangers beforehand (Baumrind, 1964).

How is it then possible that unethical experiments are allowed to take place? Do the researchers not realise that their experiments are not ethically viable? Many studies, such as the Tuskegee experiment, were not terminated by the researchers themselves (Forsman, 2002). One possible explanation is that it is difficult for the involved researchers to get an objective view of their study. They may be blinded by their aspirations to get valuable results or advance in their careers. Both ethical codes and legislation have been developed in order to avoid unethical experiments. These documents, as well as review processes, can be very useful for researchers in the planning and execution of their experiments.

3.1 Ethical codes and legislation

Many ethical codes and legislation have been developed as a response to unethical studies. As mentioned previously, the Nuremberg Code (Nuernberg Military Tribunals, 1949a) was developed as a direct reaction to experiments that were performed in Germany during the Second World War. The code is one of the first sets of ethical guidelines for medical experiments in modern times and has set the standard for more recent codes and legislation. Many of the ethical principles that are often used today can be traced back to the Nuremberg Code from the Second World War.

The basic principle of the Nuremberg Code is that participants should not suffer pain, injuries, disabilities or death as a result of medical experiments. Participants must also give their informed consent, which means that they must be properly informed about the experiment beforehand and that participation must be voluntary. Informed consent does not only mean that information must be presented to the participant, but it also requires that they understand the nature and possible consequences of the experiment. Another requirement of the Nuremberg Code is that participants must have the right and possibility to terminate the experiment at any time. The researcher also has the responsibility to end the experiment if it is suspected that it may lead to injury, disability or death.

The Nuremberg Code contains principles relating to the design of medical studies to avoid unnecessary experimentation. For example, it is required that experiments should be based on prior knowledge about the studied phenomenon and should be performed by qualified individuals. It is also stated in the code that experiments involving human participants should only be performed if it is not possible to produce the same data using alternative methods. The possible risks associated with an experiment must also be outweighed by the benefits of the results for society.

One of the most important codes for medical research today is the Declaration of Helsinki that was originally developed in 1964 (World Medical Association, 1964) and has been continuously updated (World Medical Association, 2004). The declaration contains all the basic principles of the Nuremberg Code as well as additional requirements. One important requirement is the formulation of an experimental plan for submission to an independent Ethical Review Board. The purpose of the board is to safeguard the rights and safety of participants. One right that is specifically pointed out in the Declaration of Helsinki is the right to integrity, e.g., protection of privacy and confidentiality of personal information.

According to the Declaration of Helsinki special attention should be directed at participants who do not personally stand to benefit from the experiments in which they are participating. Since these individuals are used for research without personal gain, they are an especially vulnerable group. In addition, the declaration also prohibits experiments where the included population will not benefit from the results. An example of a violation of this principle would be if participants from an African country were used in tests of medication for a typical North American ailment.

Based on the Nuremberg Code and the Declaration of Helsinki it is possible to identify five basic principles that are particularly relevant for experiments involving human participants in the field of human behaviour in fire. These principles are:

i) Restriction of harm and suffering
ii) Outweighing of risks by benefits
iii) Informed consent
iv) Right to terminate the experiment
v) Protection of integrity

The five principles stated above can also be found in other ethical codes and guidelines for research (Belmont report, 1978; CIMOS, 2002). Although the principles were originally developed for medical experiments they are often applied to other fields. In some fields, however, it is difficult to strictly adhere to the requirement of informed consent. For example, experiments in social sciences are sometimes performed in order to study people's response to stimuli, e.g., Milgram's obedience experiments (Milgram, 1963). In these types of experiments the results would be meaningless if participants were given complete information about the study beforehand. Also, experiments are sometimes the only way to get reliable and valid information. In order to deal with these problems specific ethical codes have been developed for the humanities and social sciences (APA, 1973; Vetenskapsrådet, 2002).

The Swedish Research Council has issued an ethical code for the humanities and social sciences (Vetenskapsrådet, 2002) that is highly relevant for the field of human behaviour in fire. It is written in the Code that participants should preferably be informed about the study beforehand, but also that an exception can be made if information jeopardises the experiment. If information is not given beforehand, participants must be properly informed once the experiment has come to an end. The code of the Swedish Research Council also contains specific recommendations regarding consent. In some cases, namely when the study does not deal with personal or sensitive information, the Code permits consent to be collected from a representative, e.g., an employer. However, this

requires that the experiment be part of ordinary activities and be performed during normal working hours.

Ethical codes have also been developed for video documentation (HSFR, 1996). It is often practical to use video cameras to record human behaviour in experiments. This type of documentation introduces possible violations of integrity and has hence led to the development of ethical codes. These codes typically deal with aspects related to informed consent, confidentiality and the use of video films. The basic requirements are that films not be used outside the confines of the informed consent, and that they be edited to avoid identification of participants (HSFR, 1996).

Ethical codes are mainly an aid for researchers and have no legal force. In some countries, however, there is legislation that regulates research involving human participants. An Ethics Act, which describes the ethics review process and the demands on research, was introduced in Sweden in 2004 (SFS 2003:460). The act covers research involving sensitive personal information, biological material from humans and studies with human participants. It is also specifically stated that research that is conducted according to methods that are aimed at influencing participants physically or psychologically or where there is an obvious risk of physical or psychological injury is covered by the legislation (EPN, 2008). This means that the Ethics Act is applicable to evacuation experiments.

The Swedish Ethics Act contains all five basic ethical principles stated above and has many similarities with both the Nuremberg Code and the Declaration of Helsinki. However, the principle of protection of integrity is mainly focused on sensitive personal information. Informed consent is a particularly prominent requirement in the Ethics Act and few exceptions are allowed. Virtually the only exception is research involving people that for some reason, such as illness or psychological condition, are not able to give consent. Research may, in these cases, be performed if it benefits the participants directly or other people that belong to the same population, e.g., people with the same type of illness.

Although the Swedish Ethics Act is applied to all studies involving human participants, it is strongly linked to medical research. The link to medicine is obvious in many of the supporting documents provided by the central and regional Ethical Review Boards where such terms as patient and clinical are used frequently (EPN, 2007a, 2007b). It is also clear from the Ethics Bill that the Ethics Act is focused on medical research (Regeringen, 2002). The Ethics Bill includes a description of ethical codes in other fields, but the explanation of the reasons for the proposal contains limited references to research methods and problems in fields such as the humanities and social sciences.

The Ethics Act has been criticized because it is unclear what is meant by psychological influence in the specification of the type of research that is covered by the legislation (Bergman, 2005). For example, is the Ethics Act valid for experiments where the influence is minor and short lived? This would mean that all experiments where people's response to stimuli is investigated would have to be reviewed even if the risk of injury is negligible. The ethics legislation in other countries, such as the USA, has also been criticised because it is often based on a biomedical standpoint and takes limited consideration of research methods in social sciences (Singer & Levine, 2003).

For experiments where the response of people is studied, it is often required that participants receive limited information beforehand to ensure the external validity of the results. Strictly speaking, this is a violation of the requirement of informed consent specified in the Ethics Act because participants cannot make an enlightened decision about taking part before the experiment is initiated. However, the regional Ethical Review Boards have been known to grant exceptions for unannounced evacuation experiments and have sometimes only required that informed consent be collected after the participants have evacuated (Kellner, 2006). In other cases where the evacuation is part of a company's fire drills or education, such as the office building experiments described in Paper IV, the Ethical Review Board did not require that participants explicitly give their informed consent (Branting, 2006a). Another granted exception is that participants sometimes may be given incomplete information beforehand, such as in the experiments in the Göta tunnel described in Paper III, as long as appropriate information is given as soon as possible (Branting, 2006b). These and other exceptions make it possible to apply the Swedish Ethics Act to non-medical research in spite of the rigid formulation of the legislation.

3.2 Basic ethical principles and experiments

There are many different types of evacuation experiments, but a common feature is that they can potentially violate the five basic ethical principles. It is therefore essential to explore ethical aspects of such experiments in order to identify possible points of improvement and to ensure that the study is ethically viable.

The experiment in Paper I was performed in a controlled laboratory environment, namely a tunnel for training of fire fighters. In the experiment participants walked through the tunnel that was filled with artificial smoke and acetic acid fumes, which meant that there was a potential risk of injury. The participants were given safety instructions and information about the study beforehand and they therefore knew what conditions they could expect inside

the tunnel before they entered. They could also terminate the experiment at any time by giving a signal to an observer who filmed the experiment with a thermal imaging camera.

Paper II is based on laboratory experiments and hypothetical scenario experiments. In one of the experiments participants simply looked at and graded flashing lights with different colours. The other two experiments involved participants choosing an emergency exit in a simulated fire scenario. In all three experiments the participants were given information about the study beforehand, the risk of injury was estimated to be minute and the participants were not filmed.

The field experiment in Paper III was performed in a real tunnel, namely the Göta tunnel in the city of Göteborg. Participants were recruited for the study, which meant that they had received some information prior to the experiment. The information was restricted and partly misleading in order to achieve an element of surprise. However, vital safety instructions were given to ensure the safety of participants. These instructions also included information about how participants could terminate their involvement if they did not want to continue. Video cameras were used inside the tunnel, but the participants were informed that they might be filmed.

Paper IV is based on field experiments that were performed with ordinary buildings occupants, namely with visitors in cinema theatres and employees in an office building. Since the aim of the experiments was to explore the effectiveness of flashing lights for realistic circumstances, it was not possible to inform the participants about the study beforehand. The evacuations were hence unannounced and participants received no information or instructions prior to evacuation. There was also an apparent risk of violation of personal integrity since all the experiments were filmed without prior consent from the participants.

The different experiments are associated with quite diverse ethical issues. For example, the main problem with the experiment in the Göta tunnel (Paper III) was that the participants could potentially be run over by cars and suffer serious physical injuries. The risk of severe physical injury was probably much lower in the unannounced evacuation in the office building (Paper IV) than in the tunnel experiment (Paper III). Instead, the main problem in the office building evacuation was that participants were not given any information before the experiment was initiated. This meant that participants could not give their informed consent before the evacuation. Since they did not know that they were taking part in a study, they also could not themselves terminate the experiment. Most of the experiments were also filmed (Paper I, III and IV), which meant that there was a risk that the personal integrity of the

participants could have been violated. These examples clearly indicate that there are ethical issues that need to be addressed and handled in order to ensure that evacuation experiments are ethically viable. In the following sections, ethical aspects of the experiments in the papers are examined based on the five basic ethical principles.

3.2.1 Restriction of harm and suffering

It is often explicitly stated in ethical codes and legislation that participants should not be harmed or suffer as a results of an experiment. In the case of evacuation experiments, there are undoubtedly risks that cannot be ignored. Participants can be injured both physically and psychologically, and experience great discomfort if an experiment is not planned and executed adequately. Possible dangers must therefore be identified and handled appropriately.

'Panic' and its consequences

A subject that is sometimes brought up in relation to evacuation experiments is panic and its consequences. As has been pointed out by Sime (1984), old building regulations and guidelines are often based on the assumption that panic may easily occur in the event of fire. It has also been assumed that panic can occur even if there is no direct danger (Croker, 1917; Home Office, 1934; Phillips, 1951; Roytman, 1975) and that it can spread among evacuees like a highly infectious disease (Phillips, 1951; Roytman, 1975). However, these types of statements are typically presented without arguments or empirical evidence. Sime (1980) also suggested that panic is often used to assign blame or explain an outcome of a fire accident without proper investigation into the actual conditions during evacuation.

The main problem concerning panic is the lack of a commonly accepted definition of the term. One of the most frequently used definition has been proposed by Quarantelli (1954) who defines panic as "an acute fear reaction marked by loss of self control which is followed by non-social and non-rational flight behaviour". According to Quarantelli panic is a short-lived phenomenon that consequently rarely results in trampling and crowd crush even if people temporarily loose the ability to control their emotions and actions. The definition also describes the phenomenon as non-social as opposed to anti-social. This means that people will tend to take no consideration of social aspects, e.g., the ties to family members or friends, which is different from competitive anti-social behaviour, e.g., fighting others to get out. Similarly, Quarantelli uses the term non-rational instead of irrational to point out that people do not adequately consider surrounding information, which is different from making irrational choices. Another strength of the definition of panic stated above is that it is based on observations of human

behaviour in real emergencies (Quarantelli, 1954). However, it is unclear how the definition was derived from the collected data.

Sime (1984) has pointed out that some alternative definitions of panic include the concept of irrational behaviour, but he also suggests that the term irrational is inappropriate. If people are said to act irrationally, it is implicitly assumed that they notice relevant information, which may not always be the case. For example, if everyone tries to exit through only one of many safe exits in the event of fire, the external observer would conclude that the behaviour is highly irrational. However, for the evacuees the behaviour can be quite rational since they may not be aware of other exits.

Although it may not be clear from old regulations and guidelines what is meant by the term panic, it is evident that there is a fear that panic may lead to devastating consequences (Bird & Docking, 1949; Croker, 1917; Home Office, 1934; Phillips, 1951; Roytman, 1975). These consequences, typically injury or death, are sometimes assumed to result from an undisciplined rush for exits that causes trampling or crowd crush (Phillips, 1951; Roytman, 1975). This type of behaviour is highly unlikely, as has been shown by numerous unannounced evacuation experiments (Bayer & Rejnö, 1999; Frantzich, 2001b; Shields & Boyce, 2000). People typically seem to evacuate in an orderly fashion without indication of panic, as defined by Quarantelli (1954), and without an undisciplined rush for exits. It should be added that the stimuli in typical evacuation experiments are relatively mild, e.g., only a fire alarm and no real smoke, and that there are many available exits. However, evidence from experiments with more stressful stimuli, e.g., smoke, show that participants are surprisingly calm (Latané & Darley, 1970). These results suggest that the probability that people will panic or rush for exits is negligible for typical evacuation experiments.

Physical and psychological injury

There is always a risk that evacuation experiments can lead to physical and psychological injury. Since panic and undisciplined rush for exits is highly unlikely, it is probable that injuries will be limited to a few individuals. For example, a participant may fall and hurt himself during evacuation. Although there is undoubtedly a risk that participants may be injured, it is believed that the probability of injury is small in most cases. This conclusion is supported by many evacuation experiments where participants have not been hurt (Bayer & Rejnö, 1999; Frantzich, 2001b). An interesting question, however, is whether a low probability of injury is acceptable? It is also interesting to examine the likely consequences of typical injuries.

Many evacuation experiments are similar to fire drills in that a fire alarm is activated and people evacuate. Another similarity is that both drills and experiments can be unannounced. Fire drills are often justified as a educational activity that ensures that building occupants have adequate knowledge about evacuation procedures, which is a requirement according to Swedish legislation relating to systematic fire prevention (SRVFS 2004:3) and safety in the workplace (AFS 2001:1). Fire authorities often recommend fire drills (Räddningstjänsten syd, 2007) and previous regulations about evacuation specifically state that fire drills should be performed on a regular basis (AFS 1993:56). The fact that fire drills are recommended suggests that both fire authorities and legislators believe that injuries are unlikely, or at least that the educational benefits of fire drills outweigh the risks.

The main difference between fire drills and evacuation experiments is that the experiments are typically documented more extensively. New technical installations are sometimes also tested, which means that the evacuation conditions are modified slightly. However, it is believed that the documentation and technical installations do not contribute to an increased probability of injury or to worse consequences of such injuries. Because evacuation experiments are intensely monitored and often have contingency plans in case something goes wrong, it is probable instead that experiments cause fewer and less severe injuries compared to fire drills.

Evacuation experiments are sometimes a part of the ordinary fire safety education of building occupants. This was the case for the office building evacuation (Paper IV). The experiment was part of an ordinary fire drill and the only changes to the original conditions were the flashing lights that were used at emergency exits on selected floors. Since building occupants would have taken part in a fire drill regardless of the experiment, the experiment did not increase the risk. However, it is possible that evacuation experiments are performed in addition to ordinary fire drills, which means that the overall probability of injury increases. As mentioned previously, this increase seems to be quite small based on experiences from earlier studies.

Although uncommon, it is possible that participants can be hurt in evacuation experiments. Injuries are particularly likely if the conditions are potentially hazardous, such as in the road tunnel experiments where participants interacted with traffic (Paper III). The researcher should therefore take stringent precautions in order to minimise both the probability and consequences of incidents. Likely physical injuries could be muscle strain or broken bones and psychological injuries might include anxiety disorders or depression. Many of these injuries require early intervention in order to minimise the harm and suffering. It is therefore useful to plan for possible injuries and to have

appropriate resources at hand in case of an incident. One example of proactive activities is the precautions taken during and after the laboratory experiment in the smoke-filled tunnel (Paper I). During the experiment a fire fighter with a thermal imaging camera was always present inside the tunnel. The fire fighter was instructed to assist participants if they signalled for help or if they were injured. There was also a nurse and an ambulance on constant standby during the experiment. A researcher also contacted the participants after the experiment in order to ensure that they had not suffered any psychological disorders. None of the participants reported any symptoms, but pre-planned measures were in place to provide them with help if necessary. These types of measures are sometimes recommended in ethical codes to ensure that participants do not suffer any after-effects (APA, 1973).

It may also be possible to minimise the probability of injury by taking preparative action. Certain groups of people, e.g., senior citizens or people with physical impairment, may be more likely to suffer injuries during evacuation. Some of these groups are easy to identify and can therefore be noticed by an observer who can terminate the experiment if needed. It is common practise to use observers in evacuation experiments (Bayer & Rejnö, 1999; Frantzich, 2001b) and observers were also included in all experiments of the present research. Observers were instructed to terminate the experiment if it went wrong, e.g., if there was a sign of injury or distress among participants. It is believed that this precaution leads to both lower probability of injury and helps to prevent consequences from escalating in case of an incident.

3.2.2 Outweighing of risks by benefits

One of the most important ethical principles is that the risks for participants should never exceed the benefits of an experiment. This principle can be found in both ethical codes (World Medical Association, 2004) and legislation (SFS 2003:460). Although it is difficult to directly compare risks with benefits, the principle is useful because it focuses attention on the outcomes of experiments. It is believed that many unethical experiments could have been avoided if the principle were always adhered to. One example is the Tuskegee experiment that should have been terminated when it was discovered that penicillin was an effective cure, since the discovery meant that knowledge about the natural history of syphilis became less important.

The benefits of experiments are sometimes divided into benefits to the affected participant and benefits to others (World Medical Association, 2004), Others can be, for example, society as a whole. The overall aim of many evacuation experiments is to increase the knowledge about human behaviour. This knowledge can hopefully be used to design safer buildings in the future

and society can therefore benefit from the results. For example, the experiments described in the present thesis focused on human behaviour in relation to flashing lights at exits. The results suggest that green flashing lights, if used correctly, can be an effective way to direct people to emergency exits that would otherwise not have been used. Since this type of technical installation could potentially lead to shorter evacuation time, it is easy to see possible benefits of the experiments for society.

It seems reasonable that evacuation experiments are not only beneficial to society, but also that the participants stand to benefit from taking part. As mentioned previously, there are many similarities between fire drills and evacuation experiments, see Section 3.2.1. It is commonly assumed that fire drills have a positive effect on safety, which has led to the recommendation that drills should be performed on a regular basis (AFS 1993:56; Räddningstjänsten syd, 2007). Fire authorities often agree that drills can be used to practice and evaluate emergency procedures (Lundqvist & Månsson, 2006; Räddningstjänsten syd, 2007) and thereby improve the response in a real emergency. Although it appears that few research studies have examined the effectiveness of fire drills, it is seems logical that training has a positive effect. Due to the similarities between drills and evacuation experiments, it is probable that participants also benefit from experiments because they get the opportunity to practice.

Participants are generally positive towards evacuation experiments, which suggest that they believe that the benefits outweigh the risks. This positive attitude towards experiments was noticed by Frantzich (2001b) during evacuation of three IKEA stores. The participants in Frantzich's study were asked if they thought it was good that IKEA performed evacuations with customers. Almost all participants were positive towards drills with customers. Only three of the 230 people who filled out the questionnaire believed that evacuations were not justified, i.e., that it is not suitable to perform fire drills because customers are exposed to stressful conditions. The favourable attitude towards experiments has also been confirmed by unannounced evacuation experiments in cinema theatres (Bayer & Rejnö, 1999; Frantzich, 2001b).

It seems reasonable that participants are positive towards evacuation experiments because they believe that the risks are smaller than the benefits. An interesting question, however, is whether participants are capable of making objective judgements? There are many factors that may influence people's perception of both the risks and benefits. For example, previous research suggests that the estimated likelihood of an event increases if people are told that the event has occurred (Fischhoff, 1975). Similarly, participants in an evacuation experiment that has not resulted in injury may underestimate the

probability of injury and thereby underestimate the level of risk. Although there are limitations associated with participants' judgement, it is interesting to note that they seem to believe that the risks are smaller than the benefits. The positive attitude towards experiments can be considered a prerequisite. If participants were predominantly negative, e.g., believed that the benefits do not justify the risks, it would be ethically questionable to conduct experiments.

A direct comparison between the risks and the benefits of evacuation experiments is very difficult. However, there seems to be many potential benefits of experiments for both the involved participants and others. For example, the participants learn more about evacuation and become better prepared for a real fire accident, and the research could potentially lead to safer buildings in the future. As mentioned previously, the likelihood of injuries and the consequences of such injuries are considered to be small in most cases, see Section 3.2.1. This suggests that the risks are outweighed by the benefits for typical evacuation experiments.

3.2.3 Informed consent

Most ethical codes and legislation specify that participants must give their informed consent to an experiment. Informed consent requires that participants have received and understood information about the study, including possible dangers, so that they can make an enlightened decision to take part. Information should be given before the experiment is initiated since it is not possible to decide to take part if information is only given afterwards. However, for many evacuation experiments it is not possible to give information beforehand because it would jeopardise the validity of the results. One example is the experiments in the cinema theatre (Paper IV) where information about the evacuation would have influenced the response of participants. Since the principle of informed consent is highlighted in many ethical codes and legislation, it is relevant to explore how informed consent should be addressed and handled for evacuation experiments.

As mentioned in the previous chapter, unannounced evacuation is one of the best ways to study human behaviour in the event of fire. Because participants do not receive information beforehand, the external validity of the results is high, but the fact that the experiments must be unannounced poses an ethical dilemma. This type of problem is common for experiments in social sciences and has led to the development of ethical codes that are field-specific. According to these codes informed consent can sometimes be obtained after an experiment if there is a risk that information may jeopardise the results (Vetenskapsrådet, 2002). Since this requires that everyone be accounted for and that the consent be properly documented, this approach has mainly been

used in evacuation experiments with limited numbers of participants. Evacuations of classrooms, such as the experiments by Andrée and Eriksson (2008), are ideal for this type of approach because it is possible to bring together participants after evacuation in order to obtain a written agreement.

It is not always possible get hold of all participants after an evacuation experiment, which means that it is virtually impossible to get consent from everyone. An alternative might be to get consent from a representative, e.g., an employer. Ethical codes for the humanities and social sciences sometimes allow informed consent from a representative if the study is not sensitive in nature and if it is part of ordinary activities (Vetenskapsrådet, 2002). The unannounced office building evacuation (Paper IV) is an example of this. The experiment was part of an ordinary fire drill and only moderate modifications of the original conditions were made. The Ethical Review Board did not require that participants gave their informed consent directly, given that the evacuation was performed in agreement with legislation about systematic fire prevention and safety in the workplace (Branting, 2006a).

If informed consent is not given by participants directly, it is considered imperative that the researcher ensure that the risks and violations of integrity are small. The Federal Ethics Act in the USA specifies that institutional review boards can approve modifications to the consent procedure or may waive the requirement to obtain consent if certain conditions are met (HHS, 2005). The most important condition is that the research cannot be practicably performed without the waiver or modification, which is true for unannounced evacuation experiments. It is also required that the risks be minimal, i.e., that the probability and consequences of injury or discomfort be no greater than what can be expected in daily life. This condition is also met by many evacuation experiments, as experiments are similar to fire drills and fire drills are common practice in most buildings. The Federal Ethics Act also points out that the modification or waiver should not endanger the rights and welfare of participants, which includes protection of integrity, and that people must be provided with adequate information after participation.

Experiments that are associated with apparent risks and violations of personal integrity often require that participants receive information beforehand. For example, participants sometimes need safety instructions to ensure that they do not get hurt. The experiment in the Göta tunnel is one example of this (Paper III). Because participants interacted with traffic and because of the realistic setting, e.g., a real road tunnel and smoke, it was believed that physical and psychological injury was more likely than for typical evacuation experiments or fire drills. The participants were given safety instructions and information about the study in order to prevent injury. The information was

not complete and was slightly misleading to create an element of surprise. However, the information was deemed to be sufficiently detailed to make it possible for participants to give their consent to the study before the experiment was initiated.

Ethical codes and legislation sometimes permit the consent procedure to be modified if certain conditions are met. It is typically required that the risks and violations of integrity be small if experiments are performed with participants who have not agreed to take part. It is therefore considered important that researchers strive to minimise the probability and consequences of injuries by taking preparative measures if the principle of informed consent is not strictly adhered to.

3.2.4 Right to terminate the experiment

A common ethical principle in codes and legislation is that participants should always have the right to terminate their participation (SFS 2003:460; Vetenskapsrådet, 2002; World Medical Association, 2004). The main advantage of this principle is that a participant who, for example, feels distressed, can end the experiment himself, thereby reducing discomfort and potentially avoiding psychological injuries. Termination is usually not a problem if informed consent is given before the experiment is initiated, but it becomes problematic if the evacuation is unannounced. Since participants are initially not aware that they are taking part in a study, they will lack the capacity to bring the experiment to an end. Termination will not be an available alternative because participants will probably believe that they are taking part in a fire drill or real evacuation. An interesting question is therefore how the participants should be protected if they lack the capacity to terminate the experiment themselves?

One way to improve the safety of participants in unannounced evacuations is to use observers who have the authority and ability to end the experiment. As mentioned previously, it is common practice to use observers in evacuation experiments, see Section 3.2.1. These observers can be instructed to stop the evacuation if any of the participants show signs of distress. Even if this procedure is not a substitute for the right of participants to terminate an experiment, it may help to reduce discomfort and avoid injuries. It is also a procedure that is required by the Nuremberg Code, which emphasises the responsibility of the researcher to end the experiment if he suspects that it may lead to injury, disability or death (Nuernberg Military Tribunals, 1949a). The requirement and responsibility of the researcher to terminate the experiment if necessary can also be found in other ethical codes (APS, 2007).

There may also be other reasons for people to terminate their participation in an evacuation experiment. For example, a participant might disapprove of

being filmed because he believes that it is a violation of his integrity. The objection to filming can be addressed even if the experiment is unannounced, but requires that consent can be collected from all participants. In a study by Andrée and Eriksson (2008), participants were asked to give their consent to filming of the experiment after they had evacuated. The video footage from a number of experiments had to be destroyed because participants disapproved. This meant that data were lost, but the integrity of participants was ensured. It has been argued that participants' right to withdraw their data, e.g., video films, is particularly important when the research involves deception or incomplete information to participants (Sieber, 1992), which is often the case for evacuation experiments.

No written consent to filming was collected from participants in the unannounced evacuation experiments of the present thesis. However, participants were always given information that they had been filmed and were provided with the researchers' contact information in case they had any objections or questions concerning the study.

3.2.5 Protection of integrity

Violations of participants' integrity should always be avoided in experiments. The researcher must therefore respect the right to privacy and confidentiality of personal information (World Medical Association, 2004). The main threat against integrity in evacuation experiments is often related to the use of video cameras. If an experiment is filmed there is a risk that participants can be identified, which can be considered as a violation of privacy. Identification of participants in video footage also means that identity can be linked to behaviour. This link is inappropriate because participants may feel exposed if it is revealed that they acted inappropriately during evacuation. In order to minimise these types of problems, measures should be taken to protect the integrity of participants.

One important aspect of integrity protection is the confidentiality of personal information. Detailed or sensitive data about participants are, however, not essential for the purpose of most evacuation experiments. It is therefore not necessary to collect information that can be used to identify participants. For example, the questionnaire that was used in the cinema theatre experiments (Paper IV) only contained questions about a few participant characteristics, such as age and gender, which makes it virtually impossible to trace participants. It may sometimes be required to get personal information for follow-up purposes. One example is the experiments in the smoke-filled tunnel (Paper I) where participants' contact information was documented. This was done to enable the researchers to get in touch with participants after the

experiment to ensure that they had not suffered any injuries. However, the contact details were not linked to the experimental results, which means that the identity of participants could not be connected to their behaviour.

A variety of measures can be taken to minimise the risk of identification of participants in video footage. It is sometimes recommended in ethical codes that video films be edited to prevent participants from being identified (HSFR, 1996). An alternative approach can be to use video cameras with poor resolution. This approach was approved by the regional Ethical Review Board for the office building and cinema theatre experiments (Branting, 2006a), but has also been used in all other experiments that were filmed (Paper I and III). Due to the poor resolution of the video films, the use of wide-angle lenses and the location of the cameras it is considered very difficult to identify participants based on video footage from the experiments.

It has been pointed out that storage and use of video footage are important aspects of integrity protection for research that involves video filming of participants (HSFR, 1996). The general recommendation is that films should not be used outside the confines of the informed consent given by the participants. Researchers may therefore not use collected material for new purposes if it is clearly stated in the information to participants that only one aspect will be investigated. However, vague statements about the use of video footage must also be avoided because participants have a right to know what the films will be used for. It has also been suggested that information to participants should describe who will look at the video films and how the films will be stored (HSFR, 1996).

Participants in the experiments of the present research have been given detailed information about the use of the films. For example, the participants in the cinema theatre experiments (Paper IV) were told that the footage was to be used to investigate exit choice and that it was only to be analysed by researchers in the project. It was also mentioned that the films could be shown to others when the study was presented, but that these films were to be edited to avoid identification. Participants were also informed that the tapes were going to be stored safely at the university and that they would be destroyed when all analyses had been performed.

3.3 Ethical theory

Based on the previous sections, it is clear that experiments may violate the five basic ethical principles. It is also apparent that the magnitude of these violations can be significantly decreased if appropriate measures are taken. These measures can include actions undertaken before, during and after an experiment. However, it is not obvious that it is ethically viable to study

human behaviour in the event of fire by means of experiments. In order to examine this aspect it is considered useful to discuss experiments in relation to ethical theories. The ethics of experiments is therefore examined in the following sections based on the two most common ethical theories, i.e., utilitarianism and deontology, and based on a comparative approach proposed by Nilstun (1994).

3.3.1 Utilitarianism

Utilitarianism, which belongs to the ethical theory of consequentialism, is focused on the outcome of actions. The theory is based on the assumption that actions (or inactions) can be ranked according to their consequences for the affected individuals. According to utilitarianism the total outcome is calculated by taking the sum of all consequences, where desirable consequences are positive and undesirable are negative. This means that an action that leads to undesirable consequences for few and desirable consequences for many is typically seen as ethically justified, since utilitarianism focuses on the sum of outcomes for the affected individuals.

A common feature of utilitarianism is that no distinction is made between the importance of individuals. Hence, no special consideration of specific groups, such as family or friends, is taken in the calculation of the overall outcome. Another important aspect of the theory is that only the outcomes and not the underlying objectives of an action are considered. This means that an act that is aimed at improving conditions but instead leads to suffering or death is seen as unethical. Similarly, deliberately killing a mass murderer who would undoubtedly have murdered several more people is typically considered ethical.

Many ethical codes and legislation contain parts that are linked to the theory of utilitarianism. It is stated in the Declaration of Helsinki that all research with human participants should be preceded by an assessment of foreseeable risks and burdens in comparison to the benefits for the participants and others (World Medical Association, 2004). Others may be, for example, people who stand to benefit from the results, as well as the participants' family and friends. Another example is the Swedish Ethics Act, which requires that the risks be outweighed by the scientific value of the results (SFS 2003:460). The Ethical Review Boards are also known to consider the balance between ethical risks and scientific value when they review applications (Branting, 2006a).

There exist different definitions for both relevant outcomes and affected individuals in utilitarianism. According to the classical approach, which was introduced by Bentham (1996), the consequences are measured in terms of happiness and unhappiness. Bentham used the term happiness broadly to refer to positive things, e.g., benefits and pleasure, as opposed to negative things,

e.g., mischief and pain, which he saw as contributors to unhappiness. Bentham also argued that all humans, independent of such factors as social standing and gender, have an equal right to happiness and should hence be treated identically in the calculation of the overall outcome. A common approach in modern utilitarianism is to measure the consequences in terms of the fulfilment of people's preferences. For example, Singer (1993) has proposed that the fulfilment of interests can be used as a measure of the outcomes. Singer also argues that not only humans, but other creatures also, may have interests that should be considered.

It has been suggested that the difference between classical and modern utilitarianism is not necessarily very great (Singer, 1993). A broad definition of happiness in the classical approach may include many different types of positive outcomes. It can also be expected that people prefer lives without mischief, pain and unhappiness. The preference approach of modern utilitarianism may hence have many similarities with classical utilitarianism. Due to these similarities, no attempt is made in the present thesis to extensively explore the underlying components of outcomes. Instead, it is simply assumed that the utilitarian principle of maximising consequences is applicable.

For the sake of the present discussion about utilitarianism and experiments, it is useful to define both relevant outcomes and affected individuals. As mentioned in previous sections, evacuation experiments may result in both negative and positive consequences, see Section 3.2. Possible negative outcomes include discomfort, violations of integrity, injury and death. Positive outcomes may include many benefits, such as fire safety training and safer buildings in the future.

For evacuation experiments it seems reasonable to assume that the affected individuals consist of only humans. The group of people who are likely to be most affected are the participants themselves. Participants are also the only ones who could suffer the direct negative consequences of an experiment, e.g., getting hurt during evacuation. However, if a participant is injured or killed, there can be other groups, such as friends and family, who suffer indirectly. Since the knowledge gained in the experiment can be used to improve the safety of buildings and constructions in the future, affected individuals also include a large group of people who stand to benefit from the results. The experiment may also have a positive outcome for the participants because they get the opportunity to practice and therefore become better prepared for real fire emergencies.

It is the sum of the outcomes for all affected individuals that determines if an experiment is ethically justifiable according to utilitarianism. As mentioned

previously, the negative consequences are typically limited if appropriate measures are taken. In addition, the more severe negative consequences, such as fatalities, are likely to affect very few people since undisciplined rush for exits and crowd crush is extremely unlikely. On the other hand, there are many people who stand to benefit from evacuation experiments since the results may lead to safer built structures in the future. This suggests that evacuation experiments, if properly planned and executed, can be ethically viable according to the theory of utilitarianism. However, it should be added that it is quite complicated, or even impossible, to compare positive and negative consequences directly. For example, it is difficult to compare a minor violation of integrity with increased fire safety.

Utilitarianism is sometimes criticised because it makes no distinction between individuals. According to the theory, it is ethically justifiable to kill an innocent person if it would save the lives of two other persons. This principle sometimes leads to ethical judgements that are not intuitive for most people. One example is the cold water immersion experiments of the second world war. These experiments undoubtedly caused much suffering, injury and death, but they also resulted in increased knowledge about hyperthermia. For example, it was discovered that the survival time in freezing water was prolonged if the back of the neck was protected (Nuernberg Military Tribunals, 1949a). This result has influenced the design of both life jackets and survival suits and has therefore prevented the loss of many lives. Based on a utilitarian viewpoint the cold water immersion experiments can therefore be seen as ethically viable. However, most people would agree that it was not ethically justified to perform the experiments.

When the theory of utilitarianism is strictly applied to specific cases, as in the examples above, it is often labelled act utilitarianism (Hansson, 2002). The fact that act utilitarianism sometimes leads to conclusions that are not intuitive has led to the development of rule utilitarianism. The principle of maximising consequences should be used to derive general ethical rules and not applied to specific cases according to rule utilitarianism. For example, the rule *thou shall not kill* may be a good general rule since it leads to a more secure and better society. In a specific case, however, it may not always be the optimal choice. Because rule utilitarianism dictates that there are general ethical rules it has similarities with deontology, which is discussed in the following section.

3.3.2 Deontology

Deontology is based on the assumption that people have moral duties that determine the ethical rules that should be followed. One example is the duty to inflict no harm, which makes it unethical to kill or injure other people. The

moral duties are primary and limited account is taken of the consequences of actions in deontology. For example, if it is considered unethical to harm others it is also unethical to injure someone to prevent more people from being hurt. An action is hence seen as either ethical or unethical independent of its outcome.

The moral duties are central in deontology since they determine what actions are ethical and what are unethical. Considerable effort has therefore been made by philosophers to specify and explore moral duties. One of the first coherent theories about deontology was proposed by Kant (1981), who introduced the categorical imperative. Kant argued that the categorical imperative, which (in one formulation) states that you should always act according to principles that you would be willing for everyone to follow, is unconditional and applicable to all situations. The categorical imperative can therefore be seen as a universal moral obligation. Other philosophers have also specified moral duties. Ross (1946) proposed that acts should be judged based on seven different duties, such as the duty to help and the duty not to harm other people.

It is considered essential to clearly define relevant moral duties before evacuation experiments are examined based on the theory of deontology. As was mentioned in the previous paragraph, there exist different deontological sub-theories with their own set of duties and obligations. However, for evacuation experiments it seems relevant to utilise the rules of ethical codes and legislation. For example, the Swedish Ethics Act requires that participants give their informed consent (SFS 2003:460). The researcher therefore has a moral duty to properly inform participants and to collect their consent before an experiment is initiated. Because moral duties are seen as primary in deontology, any violations of the obligation to get informed consent is seen as unethical even if the risks for participants are minimal, i.e., irrespective of the consequences. Unannounced evacuation experiments would therefore be deemed unethical according to a deontological approach that is based on the rules in ethical codes and legislation.

The moral duty of the researcher to get informed consent from participants can be derived from the deontological approaches presented by both Kant and Ross. In his second formulation of the categorical imperative, Kant (1981) suggests that one should act in such a way that people are always treated as ends and not simply as means. If an experiment is performed without informed consent it could be said that participants are used as means to achieve the researcher's goal, e.g., to increase the knowledge about human behaviour in the event of fire. The failure to obtain informed consent before an experiment is also in conflict with the duty of promise-keeping proposed by Ross (1946). According to this moral duty people have an obligation to keep

their promises to others. Ross argues that there are both explicit and implicit promises and that telling the truth is an implicit promise. Given that Ross' duty of promise-keeping is adhered to, the researcher has a moral duty to obtain informed consent from participants.

It has been suggested that violations of moral duties in deontology can be handled by introducing residual obligations. Hansson (2002) has argued that an abuse of a duty may give rise to new obligations that need to be addressed. A violation of informed consent in unannounced evacuation experiments may hence result in a number of residual obligations, such as informing participants and getting their approval afterwards. According to this view, unannounced evacuation experiments can be seen as ethically viable if all residual obligations are met. However, the view is not consistent with the theory proposed by Kant who saw many moral duties, such as the duty not to lie, as nonnegotiable.

3.3.3 Comparative approach

Both utilitarianism and deontology sometimes lead to conclusions that are not always intuitive. For example, it is typically considered ethically justified to deliberately kill one innocent person if it saves the lives of two or more persons according to utilitarianism. One bizarre example of this would be to take all the vital organs from a healthy person and give them to a number of patients who need transplants. A situation where deontology may lead to an unintuitive conclusion could involve lying. Kant has argued that lying should be considered unethical irrespective of the consequences (Kant, 1981). This means that you should not lie to someone, e.g., a murderer, even if it could have saved the lives of many people.

Although the examples in the previous section may seem extreme, they clearly show that the two theories do not always concur with the ethical judgement of people in general. This has also been pointed out by Hansson (2002) who argues that people sometimes change between a utilitarian and a deontological line of reasoning. A comparative approach, which weighs the positive and negative aspects of an experiment, can therefore be an alternative that agrees more with people's views than the two ethical theories of utilitarianism and deontology.

A comparative approach for analysing ethical conflicts in research has been proposed by Nilstun (1994). Nilstun's approach is based on three principles that he calls autonomy, benefit and justice. The autonomy principle has to do with the right to self-determination and is closely linked to the principles of informed consent, the right to terminate the experiment and protection of integrity. Benefit is used by Nilstun to represent both positive and negative consequences of research. The principle of benefit is hence a combination of

the two moral obligations not to harm and to do good things. A researcher has the responsibility not to harm participants, but he also has the responsibility to reduce suffering according to Nilstun. The reduction of suffering may be achieved by conducting relevant research.

It is interesting to note that Nilstun's approach also takes justice into account. The principle of justice refers to the fact that the benefits and burdens of research should be distributed fairly. For example, if a particular group of participants are included in an experiment they should also be the ones who reap the greatest benefits. One example of a study that violated the justice principle is the Tuskegee experiment, in which poor black men were used as participants in a study of the natural history of syphilis. The population consisting of poor black men did not stand to benefit more from the experiment than anyone else. It should be added that one of the initial aims of the study was to determine if the effects of syphilis were dependent on race (Jones, 1993). However, there was no reason to suspect any differences, which may explain why the experiment seemed to change into a general study about the natural development of syphilis soon after it was initiated.

According to Nilstun's comparative approach there are two dimensions that need to be considered when ethical decisions are made, namely the ethical principles and affected people. Before an analysis is initiated, the groups of people that may be affected must be identified. Groups that are relevant for evacuation experiments typically include participants, participants' friends and family, and people in general (society). When these groups have been identified, their ethical profits and losses are examined based on the three principles of autonomy, benefit and justice. The terms profit and loss are used broadly by Nilstun to represent the degree of adherence to the principles. For example, informed consent leads to an ethical profit and the lack of informed consent leads to a loss for participants according to the autonomy principle.

The comparative approach is considered useful for analysing ethical aspects of evacuation experiments. Table 3.1 shows the results of an analysis of an unannounced evacuation experiment in an office building, e.g., the experiment described in Paper IV. It is estimated that the office building experiment can affect mainly four groups of people, namely the participants, their family and friends, company employees and others (society). For each of the groups there are both ethical profits and losses associated with the three principles, see Table 3.1.

The office building experiment likely affects the participants the most. Since the experiment is unannounced, it is not possible to get informed consent before evacuation. The lack of informed consent can be seen as a known ethical loss for participants according to the autonomy principle, even if this

loss is partly compensated by adequate information and procedures after evacuation. Participants can also be hurt, but it is estimated that the risk of injury is not significantly increased if the experiment is part of the company's ordinary fire drills. It is also likely that the participants benefit from the evacuation because the experience may make them better prepared for a real fire accident. This suggests that the profits and losses balance out with regards to the principle of benefit. Another important point is that the participants most likely benefit directly from taking part and that the results are applicable to office buildings. This implies that the burdens and benefits are distributed fairly, which suggests a possible profit according to the justice principle.

Table 3.1. Ethical profits and losses of the unannounced evacuation experiments in the office building (Paper IV).

Affected people	**Ethical principles**		
	Autonomy	Benefit	Justice
Participants	known loss	neutral	possible profit
Family and friends		possible loss	
Employees		possible profit	
Others (society)		likely profit	

The other affected groups may also experience both profits and losses due to the experiment in the office building. Family and friends may suffer if a participant is injured or killed, which can be seen as a possible loss according to the principle of benefit. Both the employees and others (society) may benefit from the experiment, since it may reveal weaknesses in the company's evacuation procedures and because the research may lead to safer buildings in the future. This suggests that there may be profits for employees and others according to the principle of benefit.

The comparative approach is useful because it highlights the ethical strengths and weaknesses of an experiment. Nilstun (1994) argues that it is often sufficient to make an intuitive judgement based on the identified profits and losses when one attempts to come to an ethical decision about a study. Based on Table 3.1, it seems reasonable that the office building evacuation can be considered ethically viable because there are more profits than losses. However, if a study is considered controversial or if the researcher is undecided, it can be useful to conduct a more in-depth analysis of ethical aspects (Nilstun, 1994). Nilstun suggests that such an analysis should be

quantitative and should focus on the principle that is considered most important.

An interesting aspect of the comparative approach is that it allows losses to be compensated by profits. For example, the lack of informed consent can be justified by benefits for the participants and others. This approach is considered more intuitive than the strict principles of utilitarianism and deontology. Ethical Review Boards also seem to use a comparative approach when they grant exemptions from the requirements of the Swedish Ethics Act (Branting, 2006a).

3.4 Are experiments ethically viable?

The central core of the present chapter has been to explore ethical aspects of the experiments. An inventory of possible violations of the five basic ethical principles has shown that the experiments are associated with both ethical profits and losses. This conclusion poses an interesting question; Are the experiments ethically viable?

An examination of ethical theories in relation to the experiments has demonstrated that ethical judgement is highly dependent on the approach used. Experiments often appear to be justified according to a utilitarian viewpoint, but strict adherence to classical deontology may suggest that they are unethical. It therefore seems difficult to conclude whether or not evacuation experiments are ethically viable.

Although it may be difficult or even impossible to come to a generally accepted decision about the viability of evacuation experiments, it is considered essential to examine ethical aspects. This type of examination can identify possible violations and risks that can be addressed and handled by the researcher. Codes and legislation can be very useful for the researcher in this regard, since they provide the framework on which an analysis can be based. The requirements of codes and legislation clearly highlight the important ethical aspects that should be adequately considered in the design of experiments. More specifically, the five basic principles that were presented in Section 3.1 are considered highly relevant and should be included in all ethical analyses of evacuation experiments.

The Swedish Ethics Act specifies that all experiments with human participants must be subject to an ethical review (SFS 2003:460). The review is performed by a regional Ethical Review Board that includes both researchers and laymen. It is believed that the review process, which also exists in many other countries, helps to improve the ethics of evacuation experiments. The effect of the review process is twofold. First of all, it forces the researcher to identify

and examine ethical aspects of the experiment, which probably leads to better awareness of possible weaknesses. Once these weaknesses are known they can be dealt with to minimise possible ethical violations and risks. The fact that rules make researchers more aware of ethical issues has also been pointed out by Forsman (2002).

The second effect of the review process on the ethics of evacuation experiments is linked to the fact that the experiment is examined by people who are not connected to the research. Because the members of the regional Ethical Review Board are not involved in the experiment, they are likely able to maintain an objective view. The members are not blinded by such factors as their aspirations to obtain valuable results or advance their careers. In addition, the regional Ethical Review Boards in Sweden always have representatives from both the research community and the general public, which ensures that different views are considered. An ethical review process can therefore help to avoid experiments that are considered unethical.

One question that is sometimes raised is that researchers may take less responsibility for their studies if there are ethical rules and regulations (Forsman, 2002). The introduction of the Swedish Ethics Act in 2004 not only meant that experiments involving human participants had to be reviewed, but also that they were approved by a government appointed review board. An approval by a regional Ethical Review Board means that the researcher cannot be prosecuted for ethical transgressions, unless the conditions of the approval are violated. This immunity signals that an approved experiment is ethically viable according to the law. However, the final responsibility always rests with the researcher, who has to take the appropriate measures to ensure the ethical soundness of the experiment.

As has been pointed out, it may not be possible to objectively determine if an experiment is ethically viable. Nevertheless, the ethics review process is essential because unethical aspects of a study can be discovered at an early stage and addressed before any experiments are performed. Most of the experiments that are presented in this thesis have therefore been reviewed and approved by an Ethical Review Board (Paper I, III and IV). Only those experiments described in Paper II were not submitted for review because they were deemed uncontroversial from an ethics viewpoint. This judgement was based on the estimate that they only involved a minute risk of violation of the basic ethical principles.

4 Flashing lights at emergency exits

Flashing lights at emergency exits can potentially optimise evacuation of buildings and road tunnels by influencing the behaviour of occupants, e.g., their choice of exit. However, the design of such a system must be based on systematic research to ensure that it works as intended. The four papers of this thesis explore different aspects of flashing lights at emergency exits in both buildings and road tunnels according to the research strategy described in Section 2.4. In the present chapter, the studied system is discussed and the empirical findings are put in relevant context. The system is discussed in relation to design aspects and environmental factors, e.g., the social and physical setting, that were identified in the experiments. A framework (Theory of Affordances) for understanding and analysing the findings is also described.

4.1 Identified threats – Why is a system necessary?

In the first chapter, a major threat to safe evacuation in case of fire in buildings and road tunnels was identified. The threat is the tendency of people to move towards the familiar in emergencies. This tendency can lead to non-optimal use of exits because people may use the everyday entrances or exits that are further away instead of emergency exits that are closer. This type of exit choice behaviour has been observed in both evacuation experiments (Frantzich, 2001b) and real fires (Sime, 1985). An additional threat in road tunnels is that people may not want to abandon their vehicles (Shields, 2005). It is therefore important to provide motorists with the necessary incentive to make them evacuate promptly and head for emergency exits.

It seems clear there are threats to safe evacuation that can potentially be resolved by flashing lights at emergency exits. The main purpose of such a system is to influence the choice of exit. Influencing exit choice appears to be possible based on the results of the experiments described in the four papers. Although its effectiveness is not necessarily one hundred percent, it is believed that the system has great potential. However, there are a number of design aspects and environmental factors that need to be carefully considered before the system can be relied upon in real emergencies.

4.2 Design aspects

A number of important design aspects of flashing lights at emergency exits have been identified in the present research. One characteristic in particular has received much attention in the study, namely the colour of the light source, but the experiments have also revealed many other pertinent aspects. Important design aspects of the system are discussed in the following sections.

4.2.1 A simple design

An essential requirement for the design of flashing lights at emergency exits is that the system is not overly complex and difficult to understand. If the system is used in built structures that are accessible to the public, which is often the case for buildings and road tunnels, it is essential that it can be easily understood. A complex system that requires instructions prior to evacuation would be inappropriate, since it is virtually impossible to inform all possible occupants. The design should preferably rely on characteristics, e.g., symbols and colours, that have well established meanings to ensure that the system can be intuitively understood.

Not all evacuation systems can be considered as intuitive, since instructions may be required prior to use. One example of this is the tactile wayguidance system that was evaluated in experiments by SINTEF (Paulsen, 1993). The system consisted of handrails with triangular notches to indicate the direction to the closest exit. Although the notches were shaped to create the greatest resistance when moving in the wrong direction, the system would typically require some knowledge on behalf of the user. This type of evacuation system is therefore more appropriate for environments where safety instructions can be given, e.g., onboard passenger ships. However, for most buildings and road tunnels it is difficult to provide instructions, and a simple design is therefore essential.

The importance of a simple design is clearly illustrated by the experiments in the smoke-filled tunnel (Paper I). Two different types of flashing lights were evaluated in the experiment, namely orange lights next to the emergency exit sign and rows of sequentially flashing lights on each side of the exit. The rows of lights were expected to be very effective because they would convey the appropriate direction towards the closest exit. This assumption turned out to be erroneous, as none of the participants seemed to understand the meaning of the sequentially flashing lights. One likely explanation is that the system was too complex and difficult to understand, although it should be added that the sequential flashing was somewhat difficult to make out due to the dense smoke.

The responses to the questionnaire that was filled out after the experiments in the smoke-filled tunnel also confirm the importance of a simple design (Paper I). In the questionnaire participants were asked to propose a wayguidance system based on their experience in the experiment. Most of the proposed systems were simple and often consisted of combinations of symbols with well established meaning. For example, many suggested systems with arrows to guide people to emergency exits.

The green flashing lights that were tested in a road tunnel (Paper III) and real buildings (Paper IV) in Step 3 appear to comply with the requirement that evacuation systems should be simple and easy to understand. In the field experiments, the participants did not receive instructions or information about the tested system. The system still managed to influence the evacuation behaviour in many of the experiments. These results pose an interesting question; What design aspects make green flashing lights at emergency exits simple and easy to understand? Some of the answers to this question are treated in the following sections.

4.2.2 Colour of the lights

The fact that the colour strongly influences the effectiveness of flashing lights at emergency exits was discovered in Step 1, i.e., in the smoke-filled tunnel experiment (Paper I). Orange lights had been chosen for the experiment since it was believed that the colour would be easy to distinguish through smoke. However, only a few participants mentioned that they had seen flashing lights inside the tunnel and even fewer changed their choice of exit. The system hence seemed to be less effective than expected and a possible explanation is that the lights were not sufficiently encouraging. This is probably because the colour orange is typically associated with a general *warning* rather than *safety* (Paper II). The importance of the association with the colour of the lights has also been pointed out by McClintock et. al. (2001), who argue that blue flashing lights should be used due to the link to the emergency services.

The present research suggest that green is the most appropriate colour of flashing lights at emergency exits, which is largely attributed to its associations. Certain colours are known to have well-established meanings within populations (Wickens & Hollands, 2000). For example, green typically signals *safety* or *go*, whereas the contrasting colour red is associated with *danger* or *stop*. Since the studied system aims to attract people to emergency exits, it is vital to use colours that are associated with options that are positive in fire emergencies, e.g., *safety* or *emergency exit*. These types of positive associations are prominent for green flashing lights, but are less common for lights of other colours (Paper II). The colour red, in particular, should be avoided if the aim is attract people to an emergency exit since red flashing lights are mainly linked to negative associations. The conclusion that there is a link between association with colour and the effectiveness of the studied system is also supported by one of the laboratory experiments at Lund University (Paper II). The experiment revealed that more participants used an exit with flashing lights when green instead of orange was used.

Approximately eight percent of men and one percent of women in Sweden have hereditary red-green colour blindness (Nationalencyklopedin, 2008). This population may not fully benefit from the positive associations with green. The effect of colour blindness was not studied in the experiments and it is therefore difficult to conclude exactly how the condition influences people's associations. However, the vast majority of people are not colour blind and green is therefore considered to be the most appropriate colour.

One aspect that was not explicitly explored in the present research is how colour influences the discernibility of the flashing lights through smoke. Scattering of light by small particles is dependent on wavelength (Beeson & Mayer, 2008). Light of short wavelength, e.g., blue, typically scatters more than light of longer wavelength, e.g., green or red. Measurements of the dimensionless extinction coefficient, K_e, suggest that K_e is approximately constant for many fuels at wavelengths above approximately 400 nm, i.e., most of the visible colours (Krishnan, Lin, & Faeth, 2001). The dimensionless extinction coefficient can be expressed as

$$K_e = -\lambda \cdot \ln(I/I_0)/(L \cdot f_v) \qquad \textit{equation 1}$$

where λ is the wavelength of the light, I_0 is the light intensity at the origin, I is the remaining intensity when the light has travelled the path length L and f_v is the soot volume fraction. The equation (*equation 1*) describes how the intensity of a beam of light of a certain wavelength decreases as it passes through a medium with particles, e.g., soot. If it is assumed that K_e is approximately constant for visible colours, red and green light can be compared according to the expression

$$\lambda_{green}/\lambda_{red} = \ln(I_{red}/I_0)/\ln(I_{green}/I_0) \qquad \textit{equation 2}$$

which follows from combining the expressions for the dimensionless extinction coefficient of red and green light (*equation 1*) and simplifying. Both L and f_v can be removed when the two expressions are combined because they are independent of the wavelength of light. For simplicity, I_0 can be said to be identical for the two colours, which corresponds to a green and a red light source with the same light intensity. The term $\lambda_{green}/\lambda_{red}$ in the equation (*equation 2*) is approximately 0.85 for a combination of yellowish green (λ=555 nm) and red (λ=650 nm). Based on this value it can be calculated how the relative intensity difference of the green and red light (I_{green}/I_{red}) increases as a function of the relative decrease of the intensity of red light (I_{red}/I_0), see Figure 4.1. In the figure it can be seen that the term I_{green}/I_{red} is as low as 0.5 when only one percent of the red light remains. This corresponds to 50

percent of the green light remaining after passing through the same smoke as the red light. The figure hence suggests that the intensity of the light that reaches a specific person would be stronger for red than for green flashing lights, given that the original intensity is identical.

Another important aspect in relation to the discernibility of flashing lights through smoke is the wavelength sensitivity of the human eye. Research has shown that the eye is most sensitive at a wavelength of light around 555 nm (Judd & Wyszecki, 1975), i.e., yellowish green. At a wavelength of 650 nm, i.e., red, the relative sensitivity is only about ten percent. This means that the relative sensitivity difference between green and red light (V_{green}/V_{red}) is 10, which illustrates that a lower intensity at the eye of green compared to red light does not necessarily mean that green flashing lights are more difficult to discern through smoke. Although the present example is associated with a number of crude simplifications, such as ignoring ambient light and simplifying the scattering phenomena, it clearly illustrates that the colour green cannot be easily dismissed for flashing lights in smoke-filled environments.

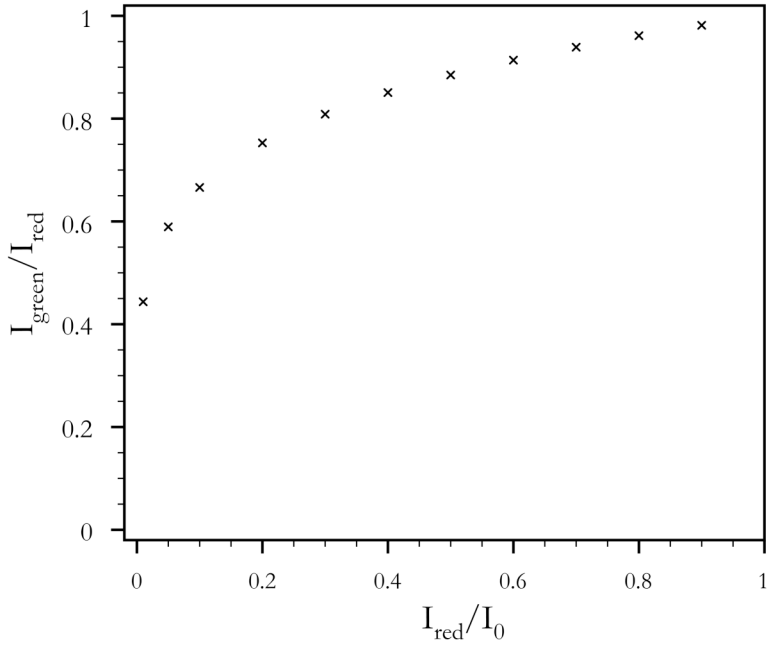

Figure 4.1 The relative difference between the intensity of green and red light (I_{green}/I_{red}) as a function of the relative decrease of the intensity of red light (I_{red}/I_0).

It should be added that flashing lights at emergency exits might not be the most optimal system in smoke-filled environments. This was clearly illustrated by the experiments in the smoke-filled road tunnel where the participants used their perception of touch rather than their vision when they tried to find an exit (Paper I). In this type of environment, a tactile system would therefore be a more effective way of directing people to emergency exits.

4.2.3 Location of the lights

When the two types of flashing lights were designed for the experiment in the smoke-filled tunnel, it was assumed that the main effect of the orange lights would be to attract attention to the emergency exit sign (Paper I). One light was placed on each side of the sign because it was believed that they would make people notice the sign, which would then convey information about the existence of an exit. It was hence not considered that the characteristics of the lights, e.g., the colour, could potentially also provide important information. The experiments have clearly demonstrated that the colour of the lights is important, but this does not mean that the location is unimportant.

It is recommended that flashing lights be placed close to the emergency exit sign because they attract attention to the sign. The importance of the placement next to the sign is illustrated by the findings from the experiments in the smoke-filled tunnel (Paper I). All the participants who used an emergency exit with flashing lights in the tunnel mentioned that they had noticed both the lights and the sign. Their behaviour, which was observed in the video films, also indicates that the combination of sign and lights was important. The participants seemed to turn their heads briefly towards the exit as they passed it and then continued to walk forward along their original path. After a short while, typically a couple of steps, they turned towards the exit as if to have a closer look. While moving towards the exit they typically also looked up at the sign and flashing lights multiple times. It should also be added that those participants who only noticed the lights did not move towards the emergency exit. The importance of the location close to the sign was also confirmed by the experiment in the Göta tunnel, where one participant specifically pointed out that the flashing light focused one's attention to the emergency exit sign.

Another argument for placing the flashing lights next to the emergency exit sign is that the lights become easier to see. One requirement according to the Swedish legislation about signs and signals (AFS 2008:13) is that emergency exit signs must be installed at appropriate heights and locations where the line of sight is not blocked by obstacles, e.g., people or furniture. It is therefore often recommended that the signs be placed high, e.g., directly above the door

(Boverket, 2006). The same line of reasoning also applies to the placement of flashing lights and an appropriate alternative is therefore to put the lights next to the emergency exit sign.

4.2.4 Type of light source

Based on the present research it is difficult to conclude what type of light source should be used. Two types of flashing lights were tested in the experiments, namely incandescent light bulbs and xenon flashlamps (strobe lights). Both light sources flashed at a frequency of approximately one flash per second. The flashing generated with the light bulbs was characterised by soft transitions between on and off, and the xenon flashlamp generated a short and distinct light pulse. When the two light sources were tested in laboratory experiments, a slightly larger proportion of participants chose an exit with flashing lights when light bulbs, instead of xenon flashlamps, were used (Paper II). The participants also associated the green light bulbs slightly more with positive associations than the green flashlamps. However, these differences were small and can be a result of other dissimilarities, e.g., the intensity of the light or the size of the lamp.

Although it is not possible to draw general conclusions about the most appropriate type of light based on the research, the results show that the light source must be evaluated in relation to the environment where it will be used. One explanation that has been offered for the poor performance of the flashing lights in the office building evacuation is that the lights were not sufficiently powerful (Paper IV). The xenon flashlamps that were used in the experiment emitted a light pulse that seemed rather faint in the brightly lit office building, which can explain why the system was seen by only a few participants. In the cinema theatre evacuations, on the other hand, the flashing light bulbs were virtually impossible not to notice due to the dim ambient lighting. The system also managed to influence everyone in the cinema theatre to use the unfamiliar emergency exit (Paper IV).

4.2.5 An active system

One of the main ideas behind the use of flashing lights at emergency exit is that it is an active evacuation system, i.e., a system that changes or activates in the event of fire. The change is that the lights begin to flash on activation of the fire alarm. This transition, together with the continued flashing, can potentially make people aware that conditions have changed. More specifically, the transition alters the appearance of the exit, which may signal to people that the emergency exit should now be used instead of the everyday exit or entrance. The importance of this type of transition has been pointed out by

McClintock et. al. (2001), who argue that people learn not to notice emergency exits because they are seldom used and that an active evacuation system with flashing lights can help to break this learned irrelevance.

Although the significance of the change to flashing was not explored in the research, the results suggest that the transition is very important. Only the field experiments included activation of the flashing lights. In the laboratory experiments the participants were led into an unfamiliar environment after they had been informed about the scenario (Paper I and II). The lights were hence already flashing when they entered the setting, which means that they did not experience activation of the system. The field experiments included the entire evacuation process (Paper III and IV) and the participants therefore either witnessed the transition directly or could conclude that the appearance of the exits changed on activation of the fire alarm. The activation of the system was most apparent in the cinema theatre evacuations because participants focused their attention on the screen, which was only a few meters away from the emergency exit with flashing lights (Paper IV). It was also in the cinema theatre evacuations that the system was most effective.

Based on the research, it is clear that the flashing is an essential feature of the tested system. This conclusion is exemplified by the cinema theatre evacuations where most participants mentioned that the flashing or flashing lights made the exit stand out (Paper IV). Flashing lights were also suggested by participants in the experiment in the Göta tunnel as a way of attracting attention to the exits (Paper III). These findings suggest that one advantage of the flashing is that it draws attention to the emergency exit by making it stand out. It is also believed that the flashing is essential because it reinforces the previously mentioned transition. Because the continuous flashing of the lights is easy to notice, most people will likely realise that the appearance of the exits has changed. This change would probably be much less obvious if a non-fluctuating light source was used.

Active evacuation systems are believed to be the key to prompt response in road tunnels. One of the threats to safe evacuation in road tunnels is that motorists are sometimes reluctant to abandon their vehicles. It is therefore essential to provide them with sufficient incentive to leave promptly and head for emergency exits. This can potentially be achieved with active evacuation systems that clearly signal the urgency of the situation. Based on the present research it is difficult to conclude if green flashing lights at emergency exits are sufficient to make motorists respond promptly. In the experiment in the Göta tunnel, the system seemed effective and some participants specifically pointed out that the system can attract one's attention to the emergency exit (Paper III). The importance of noticing the emergency exit for the decision to leave

the vehicle was pointed out by many in the questionnaire. This suggests that flashing lights can potentially shorten motorists' response times by promptly making them notice the emergency exits. Many systems, e.g., information signs, voice alarms and flashing lights at emergency exits, were tested in the experiment in the Göta tunnel. It is therefore difficult to determine if flashing light alone can make motorists respond quicker. However, the experiment did demonstrate that active evacuation systems are important because they signal to motorists that they should take action.

4.3 Environmental factors

The main focus of the research has been on different design aspects of flashing lights at emergency exits, but an evacuation system can never be studied independent of its surrounding. There are a number of environmental factors, e.g., the social and physical setting, that can influence how effective or ineffective the system will be. Two factors, in particular, have been identified in the present research, namely social influence and familiarity with the building.

4.3.1 Social influence

Previous studies suggest that people are often influenced by others and by their behaviour in fire emergencies (Latané & Darley, 1970; Nilsson & Johansson, 2009). For example, if someone starts to move towards an emergency exit, it is likely that others will follow. Similarly, inactivity of others may inhibit people from taking appropriate action. It has been argued that this type of influence, which is often called social influence, is important in most fire evacuation situations (Nilsson, 2006; Nilsson & Johansson, 2009).

Social influence is sometimes divided into a normative and an informational part (Deutsch & Gerard, 1955; Nilsson & Johansson, 2009). The normative social influence is related to the individual's desire to conform to the expectations of other people. In most cases, people want to act in accordance with what is expected and may not want to stand out or make a fool of themselves. Individuals also observe other people and their behaviour to understand the current situation. The action or inaction of others may influence people's understanding of the situation and their subsequent behaviour. This latter type of influence is called informational social influence.

The findings strongly support the idea that social influence is an important environmental factor during evacuation. This fact is exemplified by the experiment in the Göta tunnel, which revealed that the evacuation behaviour of others strongly influences the decision to leave the vehicle (Paper III). Social influence was also important for the choice of exit in the experiment.

Some participants mentioned that they had seen others walk towards the emergency exit and that they themselves just followed. These statements suggest that the influence was mainly informational, i.e., that people understood how they should act based on the behaviour of others. Social influence was also observed in the cinema theatre evacuations (Paper IV). In two of the experiments, some participants initially headed for one exit, but they later turned around and walked to the exit that others were using. This behaviour can partly be explained by the fact that people do not want to stand out or make fools of themselves, i.e., normative social influence. However, informational social influence cannot be ruled out because the behaviour of others, i.e., their choice of exit, may have signalled that the other exit was most appropriate.

The effectiveness of flashing lights at emergency exits can be influenced by both normative and informational social influence. Depending on the situation, the performance of the system can be affected by both types of social influence in either a positive or negative direction. For example, people's fear of standing out may inhibit their use of an alternative exit with flashing lights if everyone else is walking towards the everyday exit. Similarly, if someone chooses the alternative exit many others may follow because they fear that they will stand out or make fools of themselves otherwise. The fact that someone uses the alternative exit may also signal that this is an appropriate and safe choice of action, thereby encouraging more people to use it. The examples clearly illustrate the complexity of social influence and suggests that it is difficult to determine how the performance of the system will be affected in a specific situation. A system with flashing lights at emergency exits should therefore always be tested in relevant field settings, i.e., Step 3 of the proposed research strategy, before it can be relied upon in real fire emergencies.

4.3.2 Familiarity with the building

The findings of the field experiments in the office building suggest that familiarity with the building is a factor that can influence the effectiveness of flashing lights at emergency exits (Paper IV). Most participants left the floor through an exit to the central staircase instead of an exit to one of the two spiral staircases. This trend was clear even when flashing lights were used at the exits to the spiral staircases. When participants were asked why they had preferred a particular exit, they often referred to the size or capacity of the stairs. The large capacity of the central staircase was seen as encouraging and the limited capacity of other staircases was discouraging. These features are actually not a part of the external appearance of the exits, but instead require knowledge about what lies behind the door, i.e., familiarity with the building. The fact that the participants were familiar with the office building and

therefore knew that the spiral staircases were intimidating or uninviting might therefore be one of the explanations for the poor performance of the flashing lights in the experiment. The finding also suggests that flashing lights at emergency exits are no substitute for appropriate design of exit routes. If people are familiar with the building and feel uncomfortable using a particular exit route the system may not be able to influence their choice of exit. The example also illustrates the importance of testing evacuation systems in field experiments before they are used in real fire emergencies, i.e., Step 3 of the proposed research strategy.

4.4 A framework – The Theory of Affordances

The Theory of Affordances has been proposed as a useful framework for analysing the design of emergency exits (Paper IV). The theory was originally proposed by Gibson (1978) who used it to explain how people perceive things that they see. According to Gibson, people perceive objects in terms of what they can offer or afford. For example, an asphalt road is not simply seen as something that is flat and hard, but instead as something that can afford running and walking. An affordance is hence what the object offers the individuals in relation to the fulfilment of their goal. One possible goal in the event of a fire emergency is to escape, and this goal has implications for exit design. Emergency exits should ideally provide affordances that support escape, e.g., be clearly marked, distinguishable from the surrounding, easy to open, etc.

The Theory of Affordances has been used in a number of different areas that range from perception of climbing routes (Boschker, Bakker, & Michaels, 2002) to human-computer interaction design (Hartson, 2003). It has also been applied to the design of emergency exits and has been used to explain why certain designs perform poorly (Sixsmith et al., 1988). A number of attempts have been made to expand and improve Gibson's original theory and one example is the introduction of four types of affordances by Hartson (2003). Hartson argues that the affordances provided by an object, e.g., an emergency exit, can be divided into different categories depending on how they aid or support the user. The four types of affordances proposed by Hartson and the types of activities they support are:

i) Sensory affordance – sensing or seeing
ii) Cognitive affordance – understanding
iii) Physical affordance – physically doing or using
iv) Functional affordance – fulfilment of the individual's goal

The Theory of Affordances is concerned with the design of an object, e.g., an emergency exit, and how this design influences the user in a specific situation. It is therefore considered to be a useful framework for understanding and interpreting the results of the present research. In the following sections, the four types of affordances are explained, the concept of conflicting affordances is introduced and the theory is used in an attempt to interpret the empirical findings. An example of how the Theory of Affordances can be used to analyse the design of an emergency exit can be also found in Paper IV.

4.4.1 Sensory affordance

A basic requirement if emergency exits are to be used by many people is that they are easy to see. The design must therefore provide adequate sensory affordances that helps potential users to sense, i.e., see, the exit in fire emergencies. One example is that the door should be clearly distinguishable. This can be achieved by painting it in a different colour than the surrounding walls. If the door is the same colour or pattern as the walls, it is much more difficult to discern, which was clearly illustrated in a study by Sixsmith et al. (1988). In that study, it was discovered that emergency exits that were painted with murals became extremely difficult to notice, which suggests that the particular design did not provide sufficient sensory affordance.

Flashing lights can potentially improve the sensory affordance of emergency exits. It was pointed out in many of the experiments that the lights were a feature that made the exit stand out and become easy to notice (Paper III and IV). The fact that the lights flashed probably increased their attention-grabbing ability and contributed to improved sensory affordance compared to a standard emergency exit design, i.e., only a sign above the door. The location of the lights next to the emergency exit sign may also have made the lights easier to notice because they were not obscured by obstacles. In addition, their location may have helped to attract attention to the sign.

It is possible that an exit design with flashing lights that provides sufficient sensory affordance in one setting is not sufficient in another. In the experiments in the office building, few participants seemed to notice the lights (xenon flashlamps) at the emergency exits in the brightly lit environment (Paper IV). One possible explanation is that the lights did not provide enough contrast and thus not sufficient sensory affordance to be easily noticed. In this particular setting, more powerful lights may have been necessary in order to make people notice the emergency exits.

4.4.2 Cognitive affordance

Cognitive affordance supports understanding about the observed object, e.g., how it is used or what it is used for. For emergency exits, it is important that people understand that the exit should be used in emergencies and that it leads to a safe place. This information must therefore be conveyed by the design. The emergency exit sign above the door is an example of a feature that informs people about the use of the exit. It can be expected that most people are familiar with the sign and know that it signifies that the exit should be used in emergencies. If flashing lights are placed next to the sign it will become easier to discover, which may reinforce the cognitive affordance provided by the sign.

The green flashing lights that were tested in the final step of the research (Paper III and IV) seem to improve the cognitive affordance of emergency exits by making it easier for people to understand how and when to use them. It was discovered in the experiments that the green colour of the lights was linked to positive associations, e.g., *safety* and *emergency exit*. These positive associations can potentially make people understand that it is safe to use the exit. The previously mentioned transition to flashing may also help to improve the cognitive affordance compared to the standard emergency exit design. The transition, which is reinforced by the continued flashing, may inform people that it is now possible, allowed and recommended to use the exit to escape.

A complex design can make an object hard to use because people have difficulty understanding how to use it. It is therefore important that the design of emergency exits be simple and easy to understand. The green flashing lights, if noticed, seem to fulfil this requirement (Paper III and IV). In the field experiments, participants were not given any information or instructions, but they still often chose the exits with flashing lights. The system therefore seems to help people understand that the exit should be used and therefore improves the cognitive affordance compared to the standard design of emergency exits.

4.4.3 Physical affordance

Physical affordance supports the user physically doing something, such as opening the door of an emergency exit. Previous research has shown that emergency exits are sometimes difficult to open because of opening devices that require considerable force to operate (Kecklund, Hedskog, & Bengtson, 2004). Other obstacles can be that the door is locked or that a large force must be applied to open it. These types of aspects, although very important, have not been included in the present research. However, physical affordance is essential and should therefore be carefully considered when emergency exit are

designed. It is imperative that people can easily use the exit and the design should ideally support this use by being simple to operate.

4.4.4 Functional affordance

Functional affordances help users to achieve their goal, i.e., to accomplish the task they have set out to perform. One goal in fire emergencies is probably to escape as quickly as possible. Given this goal, an emergency exit that is easy to see, understand and operate would offer functional affordance by helping evacuees achieve their goal to escape quickly and safely. However, a fire blanket, although it may also be easy to see, understand and operate, would typically provide less functional affordance in this situation.

One of the main problems when examining the functional affordance of an emergency exit is that it is often difficult to identify all possible goals. As pointed out earlier, one goal is probably to escape quickly and safely, but there can also be other goals that influence people's behaviour. For example, the field experiments identified that social influence was an important factor (Paper III and IV). In particular the normative social influence, i.e., the fear of standing out or making a fool of oneself, can inhibit people from using an emergency exit instead of the everyday exit or entrance. People might also want to avoid things that they believe are unpleasant or that they feel uncomfortable with. In the office building evacuations, some participants mentioned that they avoided the emergency exits that led to the spiral staircases because the stairs were narrow or had a limited capacity (Paper IV). These findings suggest that the spiral stairs were seen as unpleasant alternatives that people wanted to avoid. The examples clearly show that people may have a variety of goals that can influence how they perceive an exit in a specific emergency.

In spite of the fact that people may have a variety of different goals, it is believed that the main goal is typically to escape. An exit should therefore support the achievement of this goal by providing a powerful combination of sensory, cognitive and physical affordances. If these affordances are sufficiently powerful, then the importance of possible conflicting goals can become very small. For example, if green flashing lights make an emergency exit easy to notice and also make it clear that it should be used, people's fear of making fools of themselves when choosing the exit may diminish.

4.4.5 Conflicting affordances

If an emergency exit is designed inappropriately, it can provide affordances that are in conflict with each other. One example of this is if a sign with the text *No Admittance* is placed on a door of an emergency exit, see Figure 1 in

Paper IV. In this case it can be unclear to people if the exit should be used in an emergency, since the *No Admittance* sign signals that the exit should not be used, while the emergency exit sign above the door signals that it should be used. There is hence a conflict between cognitive affordances in this particular situation. Another example is when the cognitive and physical affordances are not in agreement, e.g., a pull handle on a door that can only be pushed open. The latter example is sometimes labelled misaffordance (Evans & McCoy, 1998), because the handle misinforms the user about how the door should be operated. These types of conflicts between affordances should be avoided, since they can potentially inhibit people from using an exit.

It is important to use an appropriate colour of the flashing lights in order to avoid conflicting affordances. The importance of the colour was illustrated by one of the laboratory experiments at Lund University (Paper II). In the experiment, a slightly larger proportion of participants used the emergency exit with flashing lights when green instead of orange lights were used. This difference may be explained by the fact that the emergency exit with orange flashing lights provided conflicting cognitive affordances. The notion of conflicting affordances is supported by the fact that many of the participants stated that their associations with the orange lights were negative, e.g., *danger* or *do not come this way*. It therefore seems probable that the lights signalled to people not to use the exit, while the sign above the door indicated that it should be used. This conflict was most likely much less common when the green lights were used because green is typically linked to positive associations, e.g., *safety* or *go*.

The concept of conflicting affordances is considered to be very useful for understanding why certain exit designs are inappropriate. By systematically examining the sensory, cognitive, physical and functional affordances provided by a specific exit, it may be possible to identify potential conflicts at an early stage of the design process. If this procedure were used already in the first stage of the present research, it is possible that the orange flashing lights that were tested in the smoke-filled tunnel (Paper I) would have been replaced by lights with another colour. The orange lights were chosen mainly because it was believed that they would be clearly visible through smoke, i.e., improved sensory affordance. However, how the lights influenced people's understanding about the emergency exit, i.e., possible cognitive affordances, was not considered. In retrospect, this design fault could probably have been avoided if the Theory of Affordances were used.

5 Conclusions

The first objective was to develop recommendations that describe how flashing lights at emergency exits should be designed. The previous chapter, which summarises and explains the findings, contains a number of design recommendations that can be derived from the research. The most essential requirement is that the system must be simple and easy to understand, since instructions can, in most cases, not be given to people prior to a fire emergency. It is therefore essential that the flashing lights clearly signals to people that the emergency exit should be used.

The findings suggest that green is the most appropriate colour of the lights because it is often associated with things that are positive in emergencies, e.g., *safety* and *emergency exit*. These positive associations can help to attract people to the exit, whereas negative associations would be discouraging. Furthermore, it is recommended that the lights be placed next to the emergency exit sign because they then attract attention to the sign, which informs people about the exit. This position also means that the lights are not easily blocked by obstacles, e.g., people or furniture, since the signs are typically placed a certain height above the floor, e.g., above the door or close to the ceiling.

Flashing lights at emergency exits constitute an active evacuation system that should preferably be connected to the fire alarm. When a fire is detected, the lights begin to flash, which makes the emergency exit stand out and become easier to notice. The transition, together with the continued flashing, may also signal to people that conditions have changed and that the emergency exit should now be used. In road tunnels, the system can potentially also make motorists respond more promptly because it makes them notice the emergency exits.

There are a number of environmental factors, e.g., social influence and familiarity with the building, that can influence the effectiveness of flashing lights at emergency exits. The importance of such factors for people's choice of exit can differ significantly between different settings, which suggests that it is difficult to design a system that will always work as intended. For example, lights that are sufficiently powerful in one building may not provide enough contrast in another. It is therefore important to always consider environmental factors and to test the system before it is relied upon in emergency situations. This type of test can ensure that the flashing lights are easy to notice and are interpreted as intended.

According to the second objective, a framework for examining the design of emergency exits was to be proposed. The Theory of Affordances, which was used in the previous chapter for understanding and analysing the findings of

the research, is considered to be an appropriate framework for examining the design of emergency exits. The main advantage of the theory is that it focuses on how the exit supports the users to achieve their goal, e.g., to escape quickly and safely in the event of a fire emergency. By systematically exploring the sensory, cognitive, physical and functional affordances, it is possible to identify potential conflicts. These conflict between affordances should always be avoided because they can inhibit people from using the exit. The Theory of Affordances can therefore help to identify potential design faults at an early stage in the design process.

The third and final objective was to recommend a research strategy that can be used in future testing and evaluation of evacuation systems. It is believed that the strategy that was employed in the present research can also be used in the development of new systems. The approach, which is described in Section 2.4.4, is a systematic process that relies on experiments, i.e., hypothetical scenario experiments, laboratory experiments and field experiments. By going through the process of identifying design problems, solving the problems and testing the system, it is possible to obtain an evacuation system that works as intended. It is also recommended that the process be repeated multiple times to obtain the optimal design. Since the research strategy relies heavily on experiments with human participants, it is important to carefully consider ethical aspects. Many of these aspects have been discussed in Chapter 3, which can be a useful guide for researchers. It is believed that the recommended research strategy, if used appropriately, can help to improve the design of future evacuation systems and ensure that they work as intended.

6 Future research

One of the limitations of the present work is that it focuses on only one type of active evacuation system. Although a number of conclusions can be drawn about the design of flashing lights at emergency exits, it is difficult to know if these conclusions are also valid for other systems. However, the systematic three-step research strategy presented in Section 2.4.4 can be used to develop other types of evacuation systems in future studies. Such studies should also be able to reveal the degree of external validity of the conclusions.

The recommended system with green flashing lights next to the emergency exit sign seems to be able to influence people's choice of exit, but it is not necessarily the optimal design. There might be other design aspects, not explicitly evaluated in the present work, that can improve the performance of flashing lights at emergency exits. It is therefore suggested that the system be further refined in future studies through the iterative process described in Section 2.4.4. By going through the process of identifying problems, solving problems and testing the system multiple times, the design can be successively improved. Examples of aspects that can be investigated in future studies are the location of the lights, e.g., near the sign or at floor level, and the characteristics of the lights, e.g., the frequency of flashing and intensity of the light source. Another interesting study would be to perform experiments in other countries to investigate if the findings are valid for other cultural settings.

Finally, it is suggested that future studies should explore how different types of flashing lights can be combined to more effectively influence people's choice of escape routes. The present research suggests that green is the most appropriate colour for directing people to emergency exits, which is likely due to the positive associations with green. Red, on the other hand, seems to have a discouraging effect due to associations with *danger* and *stop*. If used together, green and red flashing lights could therefore potentially guide people along the safest route through the building to an exit. By using red lights at passages that can be hazardous, e.g., that lead to parts of the building where fire has been detected, and green lights at safe passages the occupants could be directed away from the fire. This type of advanced active evacuation system must be adequately explored and tested before it can be relied upon in fire emergencies.

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Appendix - Papers

Paper I Frantzich, H., & Nilsson D. (2004) Evacuation experiments in a smoke filled tunnel. *Proceedings of the 3rd International Symposium on Human Behaviour in Fire*, Belfast, UK, pp. 229-238.

Paper II Nilsson, D., Frantzich, H., & Saunders, W. (2005) Coloured flashing lights to mark emergency exits – Experiences from evacuation experiments. *Fire Safety Science – Proceedings of the 8th International Symposium*, Beijing, China, pp. 569-579.

Paper III Nilsson, D., Johansson, M., & Frantzich, H. (2009) Evacuation experiment in a road tunnel: A study of human behaviour and technical installations. *Fire Safety Journal, 44*(4), 458-468.

Paper IV Nilsson, D., Frantzich, H., & Saunders, W. (2008) Influencing exit choice in the event of a fire evacuation. *Fire Safety Science – Proceedings of the 9th International Symposium*, Karlsruhe, Germany, pp. 341-352.

Paper I

EVACUATION EXPERIMENTS IN A SMOKE FILLED TUNNEL

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ABSTRACT

Evacuation experiments were performed to investigate the walking speed and the behaviour in smoke filled road tunnels. Three types of wayguidance systems, namely flashing lights, rows of flashing lights and floor markings, were tested in the experiments. A thermal imaging infrared camera was used to observe human behaviour during evacuation. The results show a relationship between the walking speed and the extinction coefficient. The study also reveals that persons who follow a wall without emergency exits in a smoke filled tunnel may not notice exits at the opposite side, which may be devastating during a real tunnel fire. Based on the experiments recommendations are given on how tunnels can be designed to improve the fire safety and make evacuation through smoke easier.

INTRODUCTION

In recent years a number of disastrous fires in road tunnels, such as the fires in the Mont Blanc tunnel and the Tauern tunnel, have highlighted the importance of fire safety in tunnels. Both the fires in the Mont Blanc tunnel and the Tauern tunnel resulted in fatalities and all victims, who were trapped in the smoke, died due to gas toxicity (except those killed in the collision in the Tauern tunnel) [1]. In both tunnel fires some of the victims stayed in their cars while others tried to evacuate through the dense smoke. Three persons sought shelter from the smoke in an emergency call niche in the Tauern tunnel and were eventually rescued by the fire brigade. When a fire starts inside a tunnel the smoke may pose a great threat to the tunnel users, as was the case in the Mont Blanc tunnel and the Tauern tunnel. Dense smoke makes evacuation difficult and persons may get lost or lose their orientation in the tunnel. In order to make a tunnel safe with respect to fire it has to be designed in a way that makes evacuation through smoke possible. It is particularly important that the emergency exits are easy to find when the visibility is low.

To be able to design a tunnel that can be evacuated in spite of dense smoke, it is essential to know how persons behave and how they look for emergency exits in smoke filled environments. One of the earliest investigations into

evacuation through smoke was performed by Jin in the 1970s [2]. Jin carried out experiments in a smoke filled corridor and found that the walking speed decreased with increasing extinction coefficient, i.e., with decreasing visibility. The trend, which has also been confirmed in other experiments [5], was explained by the deteriorating visibility of the surrounding surfaces, which forced the subjects to slow down. Jin also reported that the behaviour at low visibilities was similar to the behaviour found in darkness, i.e., the subjects walked along touching the wall with their hands in order not to lose their orientation in the corridor [2].

One possible way to make evacuation from smoke filled tunnels easier is to install wayguidance systems, which can help the evacuees to find their way to emergency exits. Many experiments have been performed to evaluate the performance of different wayguidance systems in a variety of smoke filled environments [3,5,4,6,7,8]. An example of a wayguidance system, which preformed well under smoke filled conditions, was the system tested by Jin and Yamada [3]. The system consisted of a row of lights that flashed in sequence to convey movement. Jin and Yamada concluded that the system was a powerful tool during evacuation through smoke when the distance between the lights was less than 1 meter. The minimum distance between lights that was tested by Jin and Yamada was 0.5 meters.

Evacuation experiments, which were performed by Paulsen, have indicated that continuous markings are better than traditional signs under smoke filled conditions [4]. In Paulsen's experiments tactile continuous markings, visual continuous markings and signs were tested in a full-scale model of a section of a passenger ferry. Based on the results Paulson suggests that visual continuous markings should be used when the extinction coefficient is expected to be between approximately 0.2 and 3.5 m^{-1} ($0.1\ m^{-1} < OD < 1.5\ m^{-1}$) during an evacuation. If the expected extinction coefficient exceeds approximately 3.5 m^{-1} ($OD > 1.5\ m^{-1}$) Paulsen recommends that tactile wayguidance systems should be installed.

Evacuation experiments were performed in the present study to investigate the walking speed and the human behaviour in smoke filled tunnels. The purpose of the study was also to test different wayguidance systems, namely flashing lights, rows of flashing lights and floor markings. The results of the study were going to be used to formulate recommendations and to highlight problems relating to evacuation through smoke in tunnels.

METHOD

Participants

Thirty males and 16 females between the ages of 18 and 29 years took part in the experiments. The participants were university students and they were recruited through information meetings at the beginning of lectures. Only persons without respiratory problems or asthma were allowed to take part in the experiments and they were paid 300 SEK (approximately €35) for their participation.

The tunnel

Experiments were performed in a tunnel that is ordinarily used for training fire fighters at the Swedish Rescue Services Agency's College in Revinge, Sweden. The tunnel was approximately 37 meters long, 5 meters wide and the distance from the floor to the ceiling was between 2.5 and 2.7 meters, see figure 1. Along the centreline of the tunnel there were pillars, which supported the ceiling, and along the left wall there were two emergency exits. The exits, which were approximately 0.9 meters wide, led to an emergency escape tunnel that ran alongside the main tunnel. During the experiments one back-illuminated emergency exit sign was placed above each emergency exit and a third sign was mounted on the wall close to the end of the tunnel. The purpose of the third sign was to resemble an emergency exit, i.e., exit 3 in figure 1 was only a fictitious exit and was not connected to the emergency escape tunnel. Both the entrance and the tunnel exit consisted of four large doors, which could be opened separately.

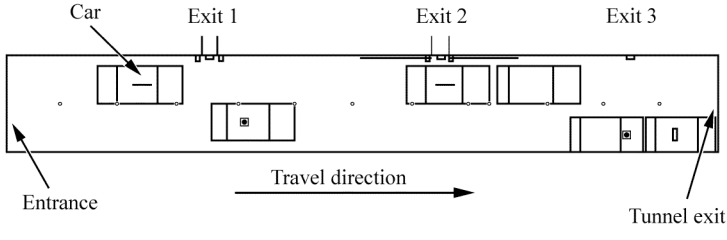

Figure 1. The tunnel used in the evacuation experiments. The third exit (exit 3) consisted of an emergency exit sign on the wall and it did not lead to the emergency escape tunnel.

Six cars were placed inside the tunnel and the cars were facing the same direction to resemble a tunnel with one way traffic. The travel direction of the cars was the same as that of the participants, namely from the entrance towards the tunnel exit, which meant that the emergency exits were located at the left wall with reference to the direction of traffic. Four of the six cars were placed close to the row of pillars and two cars were placed against the wall at the end of the tunnel, see figure 1. The distance between the tunnel wall and the cars that were placed close to the pillars was approximately 0.6 meters, which meant that it was possible for the participants to pass between the cars and the wall.

The illumination inside the tunnel consisted of five light fittings with fluorescent tubes and the illuminance at floor level was approximately 21 lx. Two large loudspeakers were placed inside the tunnel and the sound of fans and fire was played continuously during the experiments.

Artificial smoke and acetic acid

A combination of artificial smoke and acetic acid was used in the tunnel to create an environment with low visibility and irritant gases. The artificial smoke was produced by two smoke machines that used a mixture of polyglycoles and distilled water. Measurements of the light extinction coefficient were made at a height of 2.0 meters at two locations in the tunnel. The devices that were used for measuring consisted of a light source and a receiver, which were fixed 1.0 meter apart in a steel frame. The light source was a laser diode, which emitted light with a mean wavelength of 670 nm, and the receiver was a photodiode with a peak sensitivity wavelength of 710 nm. In this study the extinction coefficient, k, was calculated according to the equation:

$$k = \frac{1}{L} \cdot \ln \frac{I_0}{I} \qquad (1)$$

where I was the intensity of the light as it had passed through pathlength L of smoke and I_0 was the intensity without any smoke present.

The acetic acid, which was used to achieve irritation of the participants' eyes and noses, was boiled in pots on two electric stoves. A fan, which was used to improve the mixing of smoke and acid fumes, was placed close to the tunnel exit.

The smoke was evenly distributed in the tunnel during the experiments and the extinction coefficient was varied between 2 and 7 m^{-1}. Irritation caused by the acetic acid fumes was highest in the vicinity of the electric stoves and the maximum concentration was approximately 15 ppm. This concentration was

sufficient to cause irritation of the participants' eyes and noses without being dangerous to their health.

Wayguidance systems

Three types of wayguidance systems, namely flashing lights, rows of flashing lights and floor markings, were used in the experiments. The flashing lights consisted of orange light bulbs, which were placed at the first two emergency exits (exit 1 and exit 2). One light bulb was placed on each side of the exit doors approximately 1.9 meters above the floor and all light bulbs flashed simultaneously with a frequency of 1 Hz.

The rows of flashing lights were only used at the second exit (exit 2) and consisted of one row of light emitting diodes on each side of the exit door, see figure 2. Diodes were placed approximately five centimetres apart and flashed in sequence to convey movement towards the emergency exit. The two rows of diodes were approximately 3.7 meters long and were mounted 1.2 meters above the floor.

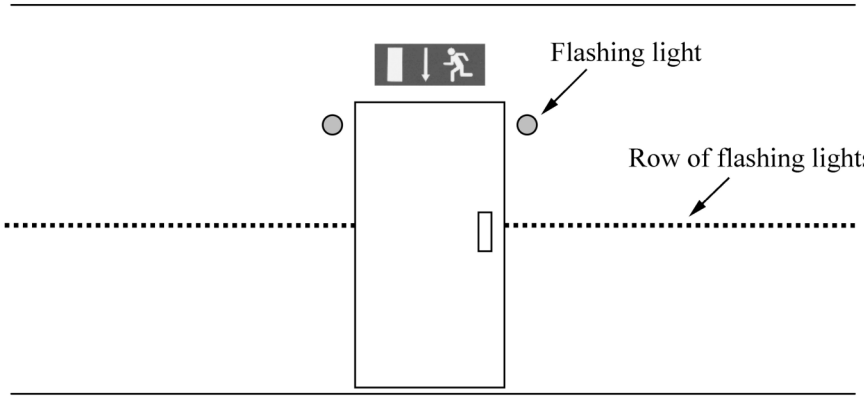

Figure 2. The flashing lights and the rows of flashing lights at exit 2

The floor markings consisted of white carpets that were placed in front the first two exits (exit 1 and exit 2). The carpets were 1.2 meters wide and stretched from the right to the left wall of the tunnel. On the carpets there were small grey arrows, which pointed towards the closest emergency exit.

PROCEDURE

The participants were given very limited information during the recruitment and briefing before the experiments. They were only told that they were going to walk into a smoke filled tunnel and that they were going to be filmed using thermal imaging infrared cameras. It was also mentioned that the smoke was irritating, but not dangerous, and that they were allowed to terminate their participation at any time by signalling for help.

The participants walked through the tunnel one at a time and no group interactions were investigated in the study. Before a participant entered the smoke filled tunnel he or she was shown a short video film. The film showed a drive into a road tunnel as seen from the driver's seat of a car. When the film had ended the participant was blindfolded and escorted to the tunnel entrance. As the participant was helped into the tunnel the following message was read (translated from Swedish):

> *You have driven into a tunnel and stopped your car. There is smoke in the tunnel and you must therefore get out. Act as you would have done in a real situation.*

After the message had been read the blindfold was removed, the entrance door was closed and the participant was free to find a way out of the tunnel. A fire-fighter was always present inside the tunnel to assist the participants if they signalled for help. The fire-fighter also filmed the participants with a thermal imaging infrared camera as they walked through the tunnel. Due to the dense smoke and the high sound level the fire-fighter could not be seen nor heard by the participants.

When the participant had exited the tunnel he or she answered a questionnaire about the experiment. The questionnaire contained background questions and questions relating to the participant's behaviour, observations and strategies. Fourteen participants were also interviewed. In the interviews the interviewees were shown a video sequence of their walk through the tunnel and were asked to explain their behaviour and their thoughts.

Two illumination levels, i.e., tunnel lights turned on and turned off, and the three wayguidance systems were combined to give five experimental scenarios, see table 1. Each participant only took part in one experiment, i.e., only walked through the tunnel once, to avoid the effect of participants learning the location of exits. The total number of participants who took part in each scenario is included in table 1.

Table 1. The experimental scenarios

Equipment	Experimental scenario				
	1	2	3	4	5
Tunnel lights	Yes	Yes	Yes	Yes	No
Emergency exit signs at emergency exits	Yes	Yes	Yes	Yes	Yes
Flashing lights	No	Yes	Yes	No	No
Rows of flashing lights	No	No	No	Yes	Yes
Markings on the floor	No	No	Yes	No	No
Number of participants in each scenario	16*	7	7	4	12

Notes: * One participant was excluded from the analysis of the results

RESULTS

Due to an error, which occurred during one of the experiments, only 45 of the 46 participants were included in the analysis of the results. Also, a technical difficulty involving the thermal imaging infrared camera resulted in one experiment being disqualified from analyses requiring video recordings. In the analysis of the results a significance level of .05 has been used for all statistical tests.

Walking speed

Video recordings from the thermal imaging infrared camera were used to determine waking speed in the smoke filled tunnel. The walking speed was calculated for each participant by dividing the total distance walked in the tunnel by the total time, and no account was taken to stops made during the walk, i.e., all stops were included in the calculations of the walking speed. In figure 3 it can be seen that the walking speed varied between 0.2 and 0.8 meters per second and that it decreased with increasing extinction coefficient.

While studying the walking speeds from the tunnel experiments it was noticed that the participants seemed to walk faster when they followed the tunnel walls. The walking speed also seemed to be dependent on the extinction coefficient, as can bee seen in figure 3. The video recordings from the experiments were used to calculate the proportion of the distance that each participant walked along the tunnel walls, which was called wall percentage. A linear regression analysis was conducted to determine if there was a relationship between the walking speed and the two variables wall percentage and extinction coefficient. Only the results from the scenarios in which the tunnel lights were turned on, i.e., scenarios 1 to 4, were included in the analysis.

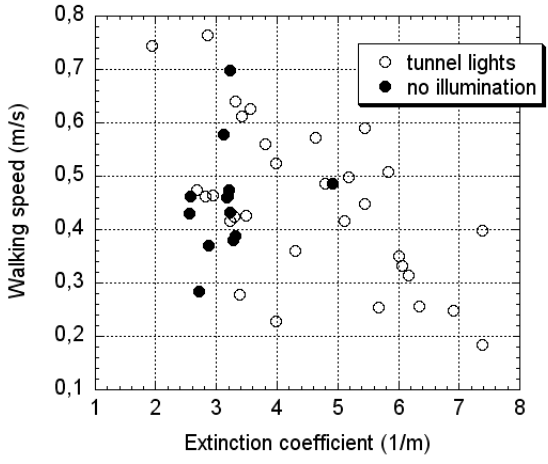

Figure 3. The walking speed in the tunnel plotted against the measured extinction coefficient when the tunnel lights were turned on and when they were turned off (no illumination).

The linear regression analysis showed a significant main effect of extinction coefficient and wall percentage on the walking speed, $F(2,29) = 12.06$, $p < .05$. Together the variables explained 42 percent of the variation in walking speed, adjusted R squared = .42. The partial regression coefficient for the extinction coefficient varied significantly from zero, $t(31) = -4.90$, $\beta = -0.73$, $p < .05$, as did the partial regression coefficient for the variable wall percentage, $t(31) = 2.44$, $\beta = .14$, $p < .05$. The analysis revealed that the walking speed decreased with increasing extinction coefficient. Also, the walking speed increased with increasing wall percentage, which suggests that the walking speed was higher when the tunnel walls were followed.

Importance of the wall

The video recordings from the experiments were used to determine the participants walking paths, see figure 4. In figure 4 it can be seen that the majority of participants walked along the walls of the tunnel. A closer analysis of the walking paths revealed that 80 percent followed the walls sometime during their walk through the smoke filled tunnel and that approximately 63 percent did not let go of a wall that they had started to follow. The most common reasons for letting go of a wall were to follow a car instead, 62 percent, or to walk towards an emergency exit sign, 15 percent.

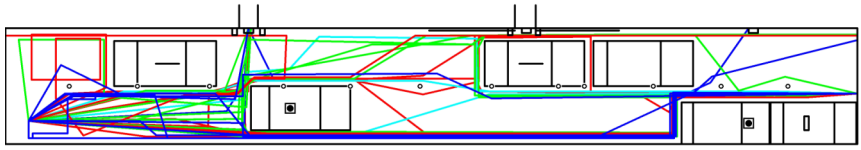

Figure 4. The participants' walking paths in the tunnel experiments

In the interviews it was revealed that the participants often tried to find a wall that they could follow in order to make it easier to find their way in the tunnel, and many of the interviewees also mentioned that they were quite reluctant to let go of a wall that they had started to follow. Five of the 14 interviewed participants said that they saw lights or flashing lights in the distance, but that they did not want to let go of the wall and walk towards the light. In the interviews it was also revealed that many of the interviewees did not actively look for emergency exits, but that they assumed that they would reach an exit if they just continued to follow the wall.

The video recordings revealed that many participants who followed the walls used their hands to look for emergency exits. The participants seemed to use their perception of touch to a greater extent than their vision when looking for exits, which was also confirmed in the interviews. Since many participants followed the right wall they did not find any emergency exits and walked the full distance from the entrance to the tunnel exit.

Emergency exits and emergency exit signs

Of the 45 participants who were included in the evaluation of the results, 34 exited through the tunnel exit and one through the entrance. Nine of the remaining ten participants walked out through the first exit (exit 1) and the last participant walked to the fictitious exit (exit 3) and was escorted out of the tunnel by the fire fighter. In all, only 22 percent of the participants walked to an emergency exit, but in the questionnaire 38 percent stated that they had seen emergency exits signs inside the tunnel. This meant that only 59 percent of those participants who saw an emergency exit sign walked to an emergency exit. An analysis of the video recordings revealed that all participants who saw a sign and did not walk towards an exit displayed signs of hesitation, such as slowing down and looking back at the sign multiple times. In contrast none of the participants who walked to the emergency exits displayed signs of hesitation.

In the questionnaire five out of seven participants stated their reasons for not using the emergency exits. Two persons mentioned that they did not believe

that the exit signs were included in the experiments, two said that they did not think that it was allowed to use the emergency exits and one stated that he had not thought about using the exits. In one of the experiments a short power failure caused the emergency exit signs to go out, which is believed to be the reason for one of the seven participants not using any of the emergency exits.

Wayguidance systems

The flashing lights were observed by six out of 14 participants, i.e., 42 percent. However, only three of the six participants who noticed the flashing lights walked out through an emergency exit. Everyone who saw the flashing lights and the emergency exit sign above the door exited through an emergency exit, but those participants who only saw the flashing lights walked to the tunnel exit.

The white floor markings were used together with the flashing lights in seven experiments. However, none of the participants in these experiments noticed any of the markings according to the questionnaires.

Sixteen participants took part in scenarios 4 and 5, in which the rows of flashing lights were used. However, only six participants, i.e., 38 percent, observed the rows of flashing lights in the experiments and no one exited through an emergency exit.

In the questionnaire the participants were asked how they would like an installation or a wayguidance system to be designed in order to make the evacuation from the tunnel easier. Thirty-four participants suggested installations and wayguidance systems that they believed would be appropriate in the smoke filled environment they had just experienced. The suggestions from the questionnaire are summarised in table 2 below. It can be seen in table 2 that the most common suggestion was signs with arrows and distances to exits or arrows and markings.

Table 2. The installations and wayguidance systems suggested by the participants

Installation or wayguidance system	Proportion
Signs with arrows and distances to exits or arrows and markings	29 %
Tunnel lights	20 %
Handrails	18 %
Row of flashing lights or row of lights	13 %
Flashing lights	9 %
Sound at the emergency exits	7 %
Other	29 %

CONCLUSION AND DISCUSSION

The results show that the walking speed decreases with increasing extinction coefficient, i.e., with decreasing visibility. This trend has also been reported by Jin [2] for extinction coefficients that were lower than approximately 1 m^{-1}. In the tunnel experiments the extinction coefficient varied between 2 and 7 m^{-1}, which makes a direct comparison with Jin's data difficult. However, the results of the tunnel experiments show that persons continue to walk despite low visibility and that the tunnel walls become very important at high extinction coefficients, i.e., low visibility. Persons who evacuate from a smoke filled tunnel tend to walk along the tunnel walls and they are often quite reluctant to let go of a wall that they have started to follow. The results of the study also suggest that persons can walk faster through smoke if they follow the tunnel walls. Since high walking speeds are favourable during an evacuation and the walls are of great importance to the evacuees, it is recommended that tunnels should be equipped with handrails. The handrails, which should be mounted on the tunnel walls, would be much easier to follow than for example a rugged rock surface.

The tested wayguidance systems were much less effective than what was initially hoped. Many participants did not observe the systems at all, which is believed to mainly be due to the low visibility in the tunnel. The white floor markings, which were not noticed by any of the participants, were hard to distinguish because of the white dense artificial smoke. It is possible that a different colour might have improved the performance of the floor markings.

Flashing lights and rows of flashing lights were noticed by some participants, but these two wayguidance systems were not very effective at directing the persons to the emergency exits. One possible explanation might be that the participants had no previous experience of the systems and did not associate them with emergency exits. This would explain why only the participants who saw a combination of flashing lights, which were less familiar, and an emergency exit sign, which was more familiar, chose to walk out through an emergency exit. The main benefit of the flashing lights was that they drew a person's attention to a sign, which conveyed information about the location of an exit.

The installations and wayguidance systems that were proposed by the participants were characterized by being simple and easy to understand, and the use of arrows to direct persons to emergency exits was a very common suggestion. An arrow is often associated with a direction towards for example an exit and an arrow might be easier to understand than other more complex wayguidance systems, such as flashing lights. Flashing lights are often ambiguous and could mean either keep away or come this way, whereas most

persons are used to following arrows. It is recommended that wayguidance systems in tunnels should be constructed in a manner that makes them easy to understand and the use of arrows to direct persons to emergency exits is strongly recommended.

One way of improving the performance of a new and unfamiliar wayguidance system may be to inform the tunnel users about the system. It is likely that the participants in the tunnel experiments would have associated the flashing lights with emergency exits if they had been properly informed. Motorists may be informed about new wayguidance systems through traffic radio, which is used in some tunnels to broadcast emergency announcements, or through clear information signs at the tunnel entrance. In train tunnels the information may be distributed through the train's internal public announcement system in case of an emergency.

A surprisingly large proportion of the participants did not use the emergency exits even though they saw emergency exit signs inside the tunnel. All persons received the same instructions before they entered the tunnel and nothing was said about what they were or were not allowed to do. It is not clear why many chose not to use the emergency exits, but one likely explanation is that the exits were unfamiliar to the participants. A person has often used tunnels many times before, but has most likely never used an emergency exit inside a tunnel. Therefore, a person might continue to walk towards the more familiar tunnel entrance or exit instead of using the less familiar emergency exits.

The tunnel experiments showed that persons who evacuate a tunnel that is filled with dense smoke use their perception of touch to a greater extent than their vision to find emergency exits. In the experiments the participants walked along the tunnel wall and tried to find exits using their hands. Similar behaviour has been reported by Jin [2] who stated that subjects began to walk with their hands touching the wall when the smoke density was increased. Many of the participants in the tunnel experiments followed the right wall and missed the exits, which were all located at the left wall. The participants were often very focused on the wall that they were following and were unaware of the exits at the opposite wall. It may not have been very dangerous for the participants to miss one or even all the emergency exits in the experiments, but missing an exit during a real tunnel fire might result in a fatal outcome. The best solution to the problem would be to install exits at both tunnel walls in all road and rail tunnels. If this measure were to be implemented persons could no longer follow the wrong wall and they would always end up at an emergency exit.

One alternative to having multiple exits may be to equip one of the walls with, for example, illuminated emergency exit signs that point towards exits at the

opposite side. In order to make the signs easier to discover in dense smoke the structure of the wall should change in those locations where signs are placed. One possibility is to place the signs in small alcoves, which are easy to discover when the walls are being followed, see figure 5. A brightly coloured line, which leads from the alcove to the exit, can be used to direct the evacuees to the emergency exit at the opposite side. Handrails can also be added to the design displayed in figure 5. It is important that the handrails end at the small alcoves and at the emergency exits. The design in figure 5 has not been tested, but it is based on the experiences from the tunnel experiments.

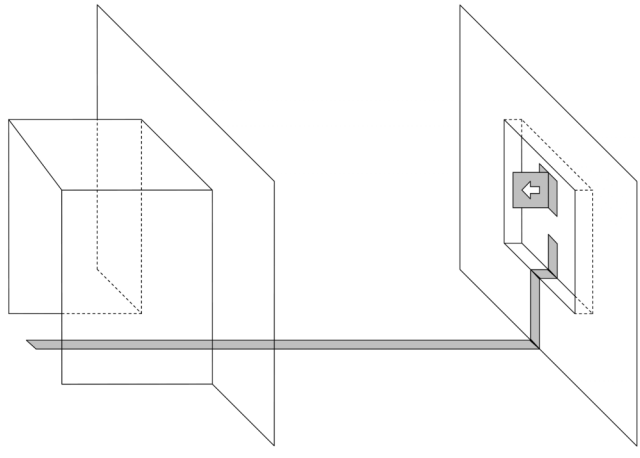

Figure 5. A suggested design of a wayguidance system in a tunnel

One of the main conclusions of the study is that persons sometimes miss the emergency exits at the opposite wall in smoke filled tunnels. Another important result is that persons use their perception of touch to look for exits when the visibility is low, which has implications on the design of wayguidance systems in tunnels. It is believed that the most effective way to make an evacuation of a smoke filled tunnel safer is to install exits along both tunnel walls. An alternative might be to design wayguidance systems that can direct persons to the emergency exits and future research can focus on testing the effectiveness of such systems.

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Paper II

COLOURED FLASHING LIGHTS TO MARK EMERGENCY EXITS – EXPERIENCES FROM EVACUATION EXPERIMENTS

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ABSTRACT

Three evacuation experiments were performed to investigate how emergency exits should be designed. In the first two experiments coloured flashing lights and strobe lights at emergency exits were tested and compared to a standard emergency exit design. In the third experiment green, blue, orange and red lights were compared to determine which colour was the most appropriate for use in emergencies. Results of the studies show that flashing lights and strobe lights, compared to the standard emergency exit design, increase the use of emergency exits. Furthermore, it is recommended that green lights should be used at emergency exits.

KEYWORDS

Evacuation experiments, emergency exit, colour, coloured flashing lights, coloured strobe lights.

INTRODUCTION

During an evacuation people will not necessarily use the closest emergency exit, but instead they might use an exit that they are more familiar with. This tendency to move towards familiar exits is often labelled affiliation or *movement towards the familiar* and was introduced by Sime [1]. The tendency to move towards familiar exits has been observed in many real fires, drills and full-scale evacuation experiments [2,3]. One example is the series of experiments that were performed by Frantzich at three different IKEA stores in Sweden [3]. In this study it was observed that people often walked past emergency exits without using them and many people exited through the main entrance or main exit. This type of behaviour may cause longer evacuation times, which in turn may result in devastating consequences in a real fire. These observations raise an important question: How should emergency exits be designed to encourage more frequent use by evacuees?

In one of the evacuation experiments at the IKEA stores it was observed that two of the emergency exits were used more frequently [3]. The only difference between these two exits and the other emergency exits was their location, relative to the marked walking path in the store. Both of the exits that were used frequently were located along the extension of the walking path, whereas all other exits were located at a ninety degree angle. This result suggests that emergency exits that are located at an angle to the natural walking path of a building might not be used very frequently during evacuation. This problem may be addressed in the design of new buildings, but in some cases, such as tunnels, it might be necessary to place exits at an angle to the direction of the natural walking path. Therefore research should examine how exits can be designed to ensure that they are used during an evacuation.

One example where movement towards familiar exits is potentially dangerous is the case of fires in tunnels. If evacuees choose not to use the emergency exits and instead use the ordinary tunnel exit, they might run out of time and perish in the smoke filled tunnel. This scenario has motivated many tunnel designers and researchers to focus on how to design exits in tunnels [4].

The problem concerning movement towards familiar exits has been addressed in a study by Mc Clintock, Shields, Reinhard-Rutland and Leslie [5]. In their study they introduced the theory of learned irrelevance as an explanation for the use of familiar exits. They also tested an alternative design for an emergency exit, which consisted of blue flashing lights that were used in combination with the European standard back-lit emergency exit sign. In the study participants were asked to compare the alternative design with five other designs, using a questionnaire-like survey. The survey revealed that the alternative design had the highest attention capturing ability and was preferred amongst the participants.

In the study by Mc Clintock, Shields, Reinhard-Rutland and Leslie, blue flashing lights were chosen, because it was believed that this colour would be associated with the emergency services in Europe [5]. This association would in turn be beneficial, because there would be a strong link between the emergency exit doors and the emergency services. However, no alternative colours were tested in the study, which gives rise to the following question: Is it possible that flashing lights of a different colour would have preformed even better than the blue flashing lights?

Certain colours are known to have established meanings within populations [6]. An example is the colour green, which often signals *go* or *safety*, and the contrasting colour red, which often signals *stop* or *danger*. Since it is desirable to attract evacuees to an emergency exit it might be important to use a colour that is associated with safety as well as with emergency exits. Using the correct

colour should further improve the effectiveness of flashing lights at emergency exits.

In order to investigate how emergency exits should be designed three experiments were performed at Lund University. The purpose of the study was to examine if coloured flashing lights and strobe lights improved the performance of an emergency exit compared to the standard design. In addition the study aimed to investigate whether green was the most appropriate colour for flashing lights and strobe lights at emergency exits. Finally, the study aimed to explore the associations with different colours in the context of emergencies.

METHOD

The following section describes three experiments that were performed at Lund University. The first two experiments were performed in August 2003. Based on these experiments one additional experiment was performed in August 2004.

Participants

The participants were new engineering students at Lund University who intended to study civil engineering, risk engineering, fire safety engineering or surveying. All experiments were performed during orientation day, that is the students' first day at University. This meant that the students had never been inside the building that was used and therefore were unfamiliar with the experiment environment. Each participant only took part once in the experiments, that is only once in one of the three experiments.

The average age of the participants was 22.2 years and ages ranged from 19 to 37 years. Table 1 presents the number of participants and the participants' ages for the different experiments. A total of 172 participants took part in the study.

Table 1. Age, gender and number of participants in the experiments.

Experiment	Age			Number of participants		
	Mean	Minimum	Maximum	Female	Male	Total
1	21.6	19	37	26	64	90
2	22.6	19	30	3	29	33
3	23.1	19	33	14	35	49
Total	22.2	19	37	43	128	172

Experiment 1 - Choice between two Exits in a Corridor

In the first experiment the participants were faced with a choice between two emergency exits, which were equipped with different way-guidance systems. The experiments were performed in a corridor in the basement of the civil engineering building, Lund University (Fig. 1). The corridor was 37.5 meters long, 3 meters wide and the height from the floor to the ceiling was 3.7 meters. Along one of the walls there were shelves, which reduced the width to 2.6 meters, and at each end of the corridor there was one exit. The lighting consisted of 4 fluorescent light tubes and the luminance at floor level varied between 3 and 72 lux along the centreline of the corridor.

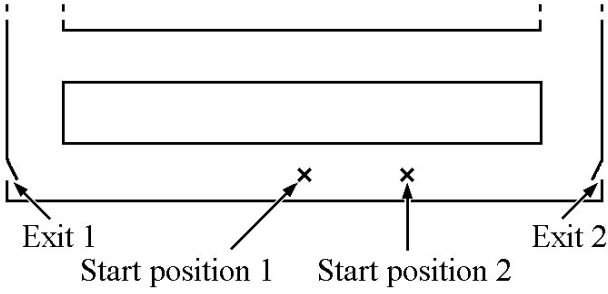

Fig. 1. The corridor used in the first experiment.

The exit doors were equipped with large windowpanes, which were covered to prevent any daylight from entering the corridor. Both exits were equipped with back-lit emergency exit signs and one of the exits (exit 1 in Fig. 1) was also equipped with additional way-guidance systems, namely different types of flashing lights and strobe lights (Fig. 2). Both orange and green lights were used in the experiments.

Fig. 2. A back-lit emergency exit sign and green strobe lights.

The start position, that is the location where the participants were placed before the experiment began, was varied. The first start position was located at an equal distance from both exits. For the second start position the distance to

exit 1 was twice the distance to exit 2. The different combination of way-guidance systems and start positions resulted in six scenarios (Table 2). In one scenario the covering was removed from the windowpanes of the door at exit 2. This was done in order to investigate if daylight influenced the participants' choice of exit.

Table 2. The scenarios for experiment 1.

Scenario	Start position	Way-guidance system at exit 1		Daylight at exit 2	Number of participants
		Flashing lights	Strobe lights		
1	1	No	No	No	17
2	1	Green	No	No	12
3	1	No	Green	Yes	17
4	2	No	Green	No	16
5	2	No	Orange	No	20
6	2	Green	No	No	8
					Σ: 90

Participants took part in the experiment one at a time and no group interactions were investigated. During the experiments an observer was always present in the corridor. Before the experiment started the participant was blindfolded, led into the corridor by the observer and placed at the appropriate start position facing the wall with exit 1 located on the left and exit 2 on the right. The participant was then told that the observer would be present, but that he or she should not take any notice of the observer and act as if he or she was alone in the corridor. Before the blindfold was removed the participant was given the following instructions:

> *Try to imagine the following scenario. You are standing alone in a long corridor and you know that there is a fire in the building, but you do not know where. You want to get out of here, because you want to get to a safe place. Please do so.*

When the blindfold was removed the participant was free to choose one of the two exits and their choice was noted by the observer, who remained in the same location throughout the experiment.

All participants completed a questionnaire after the experiment. The questionnaire contained demographic questions as well as questions relating to the experiment and to the participants' associations with different colours in emergencies. In the questionnaire the participants were asked to state what associations they had with the flashing lights or strobe lights that they had just experienced. They could choose between two positive associations, namely *safety* and *come this way*, and two negative associations, namely *danger* and *do not come this way*, or they could write down associations in their own words.

The questionnaire also contained one part in which the participants were asked about their associations to different colours in emergencies. For each colour they could choose between five alternatives, namely *Nothing in particular*, *Danger*, *Warning – Keep away*, *Warning – Look out* and *Safety*. In the questionnaire the colours green, red, orange, yellow and white where evaluated. A small box that was filled with colour was placed adjacent to each question (Fig. 3).

Fig. 3. A question relating to the participants' associations with the colour red.

The part of the questionnaire that dealt with the associations with different colours was also given to 61 third year students at Lund University who did not take part in the experiments. One question relating to the associations with blue was added to the questionnaire that was completed by the 61 students.

Experiment 2 – Choice of an Alternative Exit in a Corridor

The second experiment was performed in the same corridor as the first experiment, but the start position as well as the location of emergency exits signs and way-guidance systems were altered (Fig. 4). The emergency exit at the other end of the corridor was clearly visible from the start position and the windowpanes of the door were not covered. As the participants moved through the corridor an alternative emergency exit became visible to them on the left hand side. Both the exit at the end of the corridor and the alternative emergency exit were equipped with back-lit emergency exit signs. In addition green strobe lights were mounted at the alternative emergency exit.

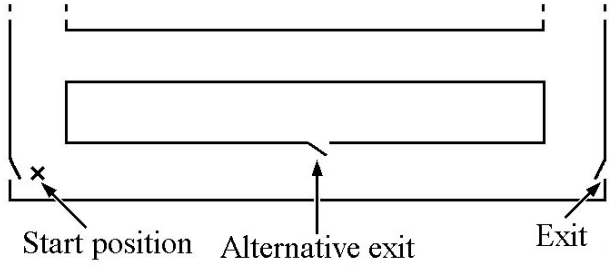

Fig. 4. The corridor used in the second experiment.

Two different scenarios were used in the second experiment (Table 3). Only one start position was used, and the strobe lights were only turned on in the second scenario.

Table 3. The scenarios for experiment 2.

Scenario	Strobe lights at alternative exit	Number of participants
1	No	16
2	Green	17
		Σ: 33

The procedure was very similar to that of Experiment 1. Participants took part in the experiment one at a time and an observer was always present in the corridor. Before the experiment started the participant was blindfolded, led into the corridor by the observer and placed at start position facing the exit at the other end of the corridor. The participant was then told that the observer would be present, but that he or she should not take any notice of the observer and act as if he or she was alone in the corridor. Before the blindfold was removed the participant was given the following instructions:

> *Try to imagine the following scenario. You are standing alone in a long corridor and you know that there is a fire somewhere behind you. You want to get out of here, because you want to get to a safe place. Please do so.*

When the blindfold was removed the participant was free to walk towards the exit at the end of the corridor. When they had walked approximately 12 meters they could see the alternative exit on the left hand side. Their choice of exit was noted by the observer, who walked a few meters behind the participant in the experiment.

After the experiment the participants completed a questionnaire that contained questions relating to the experiment as well as their associations with different colours in emergencies. The questions relating to the associations with colours were identical to the questions used in the first experiment.

Experiment 3 – A Comparison between Different Flashing Lights and Strobe Lights

In the third experiment the participants sat down in front of a display of flashing coloured lights and strobe lights. Four different colours were used, namely green, blue, red and orange. The display also included one back-lit and a front illuminated emergency exit sign.

Participants were told to imagine that the flashing lights or strobe lights were going to be used in combination with an emergency exit sign. They were then

asked to grade the extent to which they associated the different lights with an emergency exit. The degree of association was graded according to a seven point scale from *do not at all associate with an emergency exit* (1) to *associate very much with an emergency exit* (7).

RESULTS

In the following section the results of the three experiments are presented. In the analysis of the results a significance level of .05 was used for all statistical tests.

Experiment 1 - Choice between two Exits in a Corridor

The participants' choice of exit in Experiment 1 is presented in Table 4. Two participants are not included in the table because they did not choose an exit, but instead they stood still and waited for further instructions.

Table 4 shows that equal proportions of the participants used exits 1 and 2 in the scenario where no way-guidance system was used. It can also be seen that the participants had a tendency to walk towards exit 1 regardless of which way-guidance system was used at that exit. Of the 72 people who were exposed to flashing or strobe lights only 22, that is 31 percent, chose to walk to exit 2 that was only equipped with a back-lit emergency exit sign. A sign test was performed to determine if the result, that is the participants' choice of exit, was significant. The test revealed that the participants were significantly more likely to walk towards the exit that was equipped with flashing lights or strobe lights, $p = .001$.

Table 4. The participants' choice of exit in the first experiment.

Scenario	Start position	Way-guidance system at exit 1		Daylight at exit 2	Number (proportion) of participants who walked to	
		Flashing lights	Strobe lights		Exit 1	Exit 2
1	1	No	No	No	8 (50 %)	8 (50 %)
2	1	Green	No	No	9 (75 %)	3 (25 %)
3	1	No	Green	Yes	11 (65 %)	6 (35 %)
4	2	No	Green	No	12 (75 %)	4 (25 %)
5	2	No	Orange	No	11 (58 %)	8 (42 %)
6	2	Green	No	No	7 (88%)	1 (12 %)

In the questionnaire the participants were asked to state their associations with the flashing lights or strobe lights that they had just experienced. The different alternatives were classified as either positive or negative, and some participants

also wrote their associations using their own words. All the associations that the people expressed in their own words were neither clearly positive nor negative and they were thus classified as neutral.

Table 5 shows the participants' associations with the flashing lights or strobe lights and only those participants who saw the lights are included. It can be seen in the table that they associated the green flashing light with positive alternatives to a greater extent than the green strobe light, which in turn was associated to a greater extent with positive alternatives than the orange strobe light. The reverse trend is also true for the negative associations.

Table 5. The participants' associations with different types of lights.

Type of light	Number (proportion) of participants			Total number of participants
	Positive associations	Neutral associations	Negative associations	
Green flashing light	13 (72 %)	0 (0 %)	4 (22 %)	18
Green strobe light	17 (59 %)	2 (7 %)	9 (31 %)	29
Orange strobe light	5 (36 %)	2 (14 %)	7 (50 %)	14

In the questionnaires used in Experiments 1 and 2 the participants were asked about their associations with different colours in emergencies. These associations are presented in Table 6. In the table it can be seen that green was mainly associated with safety whereas red was mainly associated with danger. It is also worth noting that yellow, blue and white were generally not associated with anything in particular however yellow along with orange was associated with warning.

Table 6. The participants' associations with different colours. The association stated by more than 25 percent of the participant are underlined (__).

Colour	Danger	Warning – Keep away	Warning – Look out	Safety	Nothing in particular	Number of participants
Green	0 %	0 %	0 %	82,6 %	16,8 %	184
Red	65,2 %	17,9 %	12,0 %	2,2 %	2,7 %	184
Orange	14,1 %	24,5 %	41,8 %	2,2 %	16,8 %	184
Yellow	3,3 %	4,9 %	29,9 %	1,6 %	59,8 %	184
White	0 %	0,5 %	0,5 %	14,7 %	83,2 %	184
Blue	1,6 %	0 %	1,6 %	14,8 %	77,0 %	61

Experiment 2 – Choice of an Alternative Exit in a Corridor

Eight out of the 33 participants who took part in the second experiment did not react after they had received the instructions and required prompting again before they started to move towards the exit. These eight participants were

therefore excluded in the analysis of the results. The exit choice of the remaining 25 participants is displayed in Table 7. It can be seen that a greater proportion of the participants who were exposed to the green strobe lights used the alternative exit.

Table 7. The participants' choice of exit in the second experiment.

Scenario	Number (proportion) of o walked to		
	Strobe lights at alternative exit	Alternative exit	Exit at the end of the corridor
1	No	6 (55%)	5 (45%)
2	Green	13 (93 %)	1 (7 %)

Experiment 3 – A Comparison between Different Flashing Lights and Strobe Lights

The participants in the third experiment graded their associations with an emergency exit for four strobe lights and four flashing lights. The scale used consisted of 7 steps, where 1 was the lowest level of association and 7 was the highest. Based on the participants' ratings, calculations were performed to identify when the green flashing light was associated more, equal or less with an emergency exit, than the red, orange and blue flashing lights (Table 8). The same calculations were performed for the strobe lights (Table 9). It can be seen in Table 8 and 9 that more participants rated green higher than red, orange and blue, for both the flashing lights and strobe lights.

Table 8. The number of participants who associated the green light more, equal or less with an emergency exit for the flashing lights.

Other light	Number of participants			Results from the sign test
	Green more	No difference	Green less	*P*
Red	25	9	13	.073
Orange	27	7	14	.060
Blue	29	13	7	<.001

Table 9. The number of participants who associated the green light more, equal or less with an emergency exit for the strobe lights.

Other light	Number of participants			Results from the sign test
	Green more	No difference	Green less	*P*
Red	27	8	12	.024
Orange	25	6	16	.211
Blue	30	13	5	<.001

Six sign tests were performed to determine whether the green flashing lights and green strobe lights were generally associated more with an emergency exit than the other type of lights. The results of the significance tests are reported in Table 8 and 9. It can be seen in the tables that both the green flashing light and the green strobe light were significantly more often associated with an emergency exit than the blue lights. The result for the red strobe light was also significant, but all other results in Table 8 and 9 were not significant. (The authors recognize that multiple significance tests using the same data may increase the risk of rejecting null hypotheses although they might be true. This problem can partially be addressed by reducing the significance level.) No significant differences were found between the participants' associations with flashing lights versus strobe lights.

DISCUSSION AND CONCLUSIONS

The results of the study show that emergency exits that are equipped with flashing lights or strobe lights are chosen more frequently than ordinary emergency exits, that is exits that are only equipped with an emergency exit sign. This suggests that flashing lights or strobe lights will increase the use of an emergency exit compared to the standard design, and thereby make emergency exits better. The effectiveness of the combination of emergency exit signs and flashing lights has also been demonstrated by Mc Clintock, Shields, Reinhard-Rutland and Leslie in a previous study [5].

The purpose of the second experiment was to investigate if green strobe lights could influence the use of an alternative exit during evacuation. In the experiment a greater proportion of the participants used the alternative exit when strobe lights were used. This result implies that flashing lights and strobe lights may be an effective way of making people notice and choose alternative exits that become visible to them as they move through the building. By actively making people aware of alternative exits it may be possible to break the tendency of movement towards familiar exits.

It is believed that the main benefit of the flashing lights and strobe lights is that they direct the evacuees' attention to and make them notice emergency exit signs, which in turn convey the information about the presence of an exit. This belief has also been presented previously by Frantzich and Nilsson in a study on evacuation from smoke filled tunnels [4]. In that study it was found that only those people who saw flashing lights in combination with an emergency exit sign walked out through an exit, whereas those who only saw the flashing lights did not. Although it is believed that the information about the existence

of an exit is mainly conveyed through the sign, it is postulated that the colour of the flashing lights influences how well the way-guidance system works. Certain colours are known to have well established meaning [6]. Green often implies safety or go and may therefore be more appropriate to use than for example red, which often signals danger or stop. It is probable that green flashing lights will encourage people to look towards the sign and use the exit, whereas red might be discouraging. In the present study it was confirmed that green was associated with safety and that red was associated with danger, in emergencies. It was also apparent that yellow, white and blue were associated with *nothing in particular* and that yellow and orange were associated with different degrees of warning.

In the study by Mc Clintock, Shields, Reinhard-Rutland and Leslie blue flashing lights were used and it was hypothesised that this colour would be associated with the emergency services [5]. This association would in turn be beneficial, because there would be a strong link between the emergency exit doors and the emergency services. However, in the third experiment of the present study the blue flashing lights and strobe lights were rated significantly lower than the equivalent green lights, which implies that people are more likely to associate green lights with an emergency exit. The same trend was observed for red and orange lights, but these results were not significant. Furthermore, the colour blue was generally associated with nothing in particular in the context of emergencies, although it should be noted that the association with the emergency services was not one of the alternatives provided to respondents. Given these results, it is possible that the explanation provided in previous studies, for the success of the flashing blue lights, in terms of a link between the emergency services and emergency exit, may not be completely correct. Instead, it is possible that the blue flashing lights performed well mainly because they were the only flashing lights tested in the study.

In the first experiment the participants were asked to state their associations with the flashing lights and strobe lights to which they had been exposed. The results show that the participants' associations with the green lights were positive and their associations with the orange lights were negative. Also, it can be seen in the results of scenario 4, 5 and 6 that a higher proportion of the participants walked to exit 1, that is the exit equipped with the additional way-guidance system, for the green flashing lights. The only difference between these three scenarios is the colour of the lights that were used at exit 1.

The results of the study show that flashing lights and strobe lights increase the use of an emergency exit compared to the standard emergency exit design. This conclusion has implications for the design of exits in buildings and it is

recommended that all emergency exits should be equipped with green flashing lights. Green is believed to be the most appropriate colour, because it is interpreted as safety and go. As has been pointed out in previous research [5] the flashing lights must only activate when the building is going to be evacuated thus making it suitable to connect the system to the evacuation alarm. By installing flashing lights at all the emergency exits it may be possible to direct people to the desired exits and hence break the trend of movement towards familiar exits. Future research should focus on testing way-guidance systems in real buildings to investigate to what extent flashing green lights can influence peoples' choice of exit during evacuation.

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Paper III

EVACUATION EXPERIMENT IN A ROAD TUNNEL: A STUDY OF HUMAN BEHAVIOUR AND TECHNICAL INSTALLATIONS

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ABSTRACT

An evacuation experiment was performed in a road tunnel in order to investigate how motorists behave and emotionally respond when exposed to a fire emergency, how information and wayfinding systems are perceived and whether green flashing lights can influence exit choice. The participants believed that they were taking part in a study about driving behaviour. Approximately 1 km inside the tunnel participants encountered an accident, i.e., cars and smoke. The fire alarm, which consists of a pre-recorded alarm and information signs, was also activated and green flashing lights at emergency exits were started. The results show that it was difficult to make out what was said in the pre-recorded alarm. However, an acoustic signal was positive since it alerted motorists and made them look for additional information. The information signs were also important for the decision to leave the vehicle. Social influence was found to be essential, both with regards to the decision to leave the vehicle and the choice of exit. The results also suggest that arousal level influences the amount of information noticed by motorists, which implies that technical installations, e.g., wayfinding systems, should be tested under stressful conditions before they can be relied upon in a real tunnel fire.

KEYWORDS

Tunnel fire, evacuation; pre-recorded alarm, information signs, green flashing lights, social influence, emotional state.

1. INTRODUCTION

Disastrous fires in road tunnels, such as the fire in the Mont Blanc tunnel and the fire in the Tauern tunnel, have clearly shown the importance of effective and prompt evacuation. An important finding in this regard is that motorists do not necessarily evacuate their vehicles [1,2]. This is exemplified by the fire

in the Mont Blanc tunnel where most of the victims were found inside or near their vehicles.

It has been argued that the tendency not to evacuate the tunnel, i.e. to stay in one's vehicle, results from person and place affiliation [2]. According to the theory of affiliation in fire entrapment settings people will be attracted to and move towards familiar persons and places during evacuation [3]. In a tunnel it is possible that the vehicle constitutes something familiar, whereas the tunnel is an unfamiliar environment. Another possible explanation of the reluctance to leave the vehicle is that people do not initially want to abandon their property. A car or truck is often a large investment that people might not want to leave unattended inside a road tunnel if the situation is not perceived as being dangerous.

Thus there appear to be behavioural constraints that must be dealt with to ensure that as many motorists as possible leave their vehicles. Provision of clear information about the emergency and instructions about how to act would probably do much to improve motorist response. Research about information to motorists during tunnel fires is at present very limited. A substantial amount of research has, however, been carried out on evacuation from buildings [4,5,6]. This research has shown that information is vital during evacuation. Proulx and Sime [4] have explicitly demonstrated the importance of clear information, showing that clear messages that conveyed what had happened in an underground railway station led to shorter evacuation times than did less informative alarm bells.

Studies of evacuation from buildings have shown that evacuees do not always use the closest emergency exit [6]. According to the previously mentioned theory of affiliation, one explanation for this phenomenon is that people move towards familiar places in the event of a fire emergency [3]. In most cases the emergency exits are unfamiliar and seldom used by the occupants of a building. The emergency exits in a tunnel may similarly be even more deterring and unfamiliar than the tunnel itself. Different types of wayfinding systems have been proposed as means for influencing exit choice in emergencies [7,8]. Flashing lights at emergency exits is one example of a relevant system that has been evaluated in several studies [9,10,11]. It has been argued that green lights should be used since green is associated with safety and go, whereas the colour red and orange should be avoided [9]. Various types of systems are used to inform motorists in case of fire emergencies in tunnels, including information signs and pre-recorded alarms [12]. Although such systems have been installed in many new as well as older tunnels, research is limited regarding motorists' perception of the systems and the information conveyed.

Fires are perceived as very stressful and in an emergency situation people's emotional state is likely to influence how the individual interprets the situation and acts upon emergency information [13,14]. Emotional state can be described as the individual's immediate reaction to a situation. Theories of environmental psychology assume a continuing interaction between human and environment [15]. The Human–Environment Interaction model (the HEI model) provides a suitable tool to understand individual responses in a certain situation in a specific environment since it offers a holistic perspective [16]. The HEI model accounts for characteristics both of the physical and the social environment, and the individual's responses is further assumed to be mediated by personal factors such as demographic characteristics and personality traits. In the event of a tunnel fire the individual responses may be behavioural, e.g., exit choice and pre-movement time, perceptual, e.g., perception of technical installations, and emotional, e.g., emotional state.

According to the HEI model the present emotional state will affect people's perception of various environmental factors and thereby influence their action in a certain situation. The performed behaviour may, with regard to the physical and social environment as well as personal factors, in turn induce a shift in the individual's emotional state [16,17]. In the event of an emergency it therefore seems likely that a person's perception of the situation, such as interpretation of emergency information and other people's actions, as well as his or her subsequent behaviour, i.e., decision to evacuate, choice of exit and pre-movement time, partly is a result of how he or she feels at the time. Similarly, if and how the person chooses to evacuate may influence his or her emotions after the evacuation.

The emotional state is described as a four-step basic emotional process linked to the neuropsychological operation of the central nervous system [16]. The process includes the components activation/arousal (the strength of the emotion), orientation (how directed the emotion is), evaluation (the hedonic tone of the emotion) and control (the control of the situation). In the HEI model emotions are seen as combinations of different levels of those four components. The HEI model has previously been applied in studies of people's response to various kinds of environments.

Although reports of actual tunnel fires offer valuable information about human behaviour, they usually do not provide in-depth data about the evacuation process. For more thorough and systematic studies, however, experimental methods are required that allow for observations of behaviour under realistic conditions. Such research involving evacuation experiments is scarce for road tunnels. One exception is the study performed by Boer [18,19] in which nine experiments were performed in the Benelux tunnel in

Rotterdam, the Netherlands, in order to study human behaviour in the event of fire and to measure the time until motorists start to evacuate. The experiments in the Benelux tunnel revealed that social influence was an important factor, i.e., that motorists influence each other during evacuation, and that the closest emergency exit was almost always used [19].

In order to study human behaviour in road tunnels an evacuation experiment with partially informed participants was performed in the Göta tunnel in the city of Göteborg, Sweden [20,21]. The objective of the experiment was to:

(i) find out if motorists evacuate when exposed to a fire emergency,
(ii) quantify the evacuation time, particularly the time until people leave their vehicles,
(iii) obtain insight into factors influencing the decision to leave the vehicle and the choice of exit,
(iv) obtain information about motorists' perception of the fire alarm, namely information signs and pre-recorded alarm,
(v) obtain information about motorists' perception of green flashing lights at emergency exits and obtain insights into the ability of the lights to influence the choice of exit, and
(vi) find out if emotional state is linked to evacuation behaviour and response to evacuation information.

2. METHOD

2.1. Participants

The participants were recruited from among employees and external consultants working for the Swedish Road Administration (SRA). Care was taken to ensure that no participants had any direct involvement in the Göta tunnel building or planning process. The means of recruitment were posters on notice boards, e-mails and information at meetings. Everyone who signed up for the experiments filled out a Hospital Anxiety and Depression (HAD) questionnaire [22]. In order to exclude sensitive individuals, only those who received a score of less than eight for both anxiety and depression were included in the experiment.

Twenty-nine participants took part in the experiment, namely 27 men and two women. The age of participants spanned between 25 and 65 years, with one person not stating age. The average age was 44 years and the standard deviation was 13 years. SRA reimbursed participants by regarding the experiment as work activity. This meant that the participants and their vehicles

were insured by SRA and that they received salary according to standard agency policy.

2.2. The tunnel

The Göta tunnel is a 1.6 km twin bore tunnel with 15 emergency exits (see Fig. 1). During normal operation the traffic flow in the two tubes is uni-directional. There are either two or three lanes in each tube depending on the exact location in tunnel. In addition, there is a wide shoulder where vehicles may stop in case of a breakdown. The experiment took place at a location where there were three lanes. Emergency exits are numbered from 1 to 15 from south to north. The distance between exits is 100 m. Since the tunnel is a twin bore tunnel, the exits are located on the left walls and lead to the other tube. Twelve of the emergency exits open out into traverse tunnels that connect the two tubes, and three lead directly to the other tunnel tube. The emergency exits closest to the participants in the experiment lead to traverse tunnels.

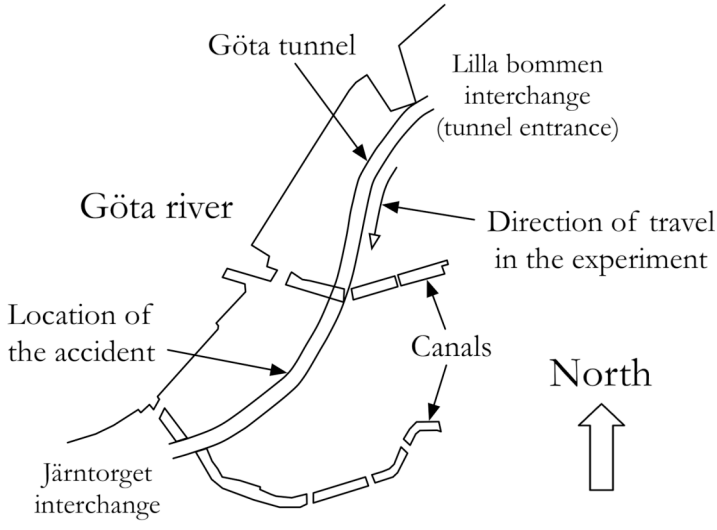

Fig. 1. The Göta tunnel.

All emergency exits are clearly distinguishable (see Fig. 2). They are located in smooth alcoves in the tunnel walls, which are covered with white ceramic tiles. The area around an exit is covered with blue ceramic tiles. To the right of each exit are blue and white tiles showing large exit numbers, which are easy to distinguish when driving through the tunnel.

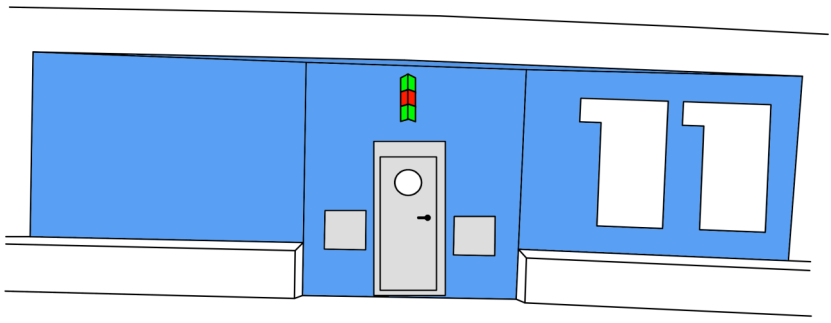

Fig. 2. Emergency exit number eleven.

The wayfinding systems in the Göta tunnel consists of back-lit emergency exit signs on the left wall in both tubes and above emergency exits. All the wall signs point towards the tunnel entrance and the distance between them is 20 m. There are also signs with the symbols for fire extinguisher and emergency phone above emergency exits. A green flashing light was placed underneath the exit signs at emergency exits six and eight (see Fig. 3). These lights were only used in the experiment and are not a standard feature of the exits.

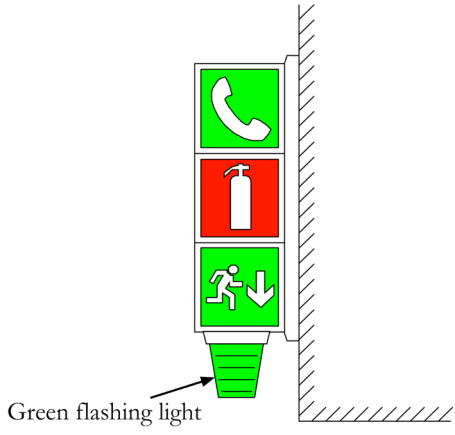

Fig. 3. The green flashing light underneath the signs at emergency exits six and eight.

The fire alarm consists of both information signs at ceiling level and a pre-recorded alarm that is played using the tunnels public announcement system. When the fire alarm is activated a message, which instructs motorists to turn off the engine and evacuate the tunnel, is displayed on the signs (see Fig. 4). In addition, two orange lights on the sign begin to flash. The pre-recorded alarm

begins with a sharp pulsating tone signal, which is followed by a message in Swedish. The message, which informs motorists that there has been a serious accident and instructs them to leave their vehicle and evacuate the tunnel, is repeated twice and followed by an English and a German version. All messages were recorded by women who are native speakers. The pre-recorded alarm is repeated and the message on the sign is displayed until the fire alarm is stopped.

Fig. 4. An information sign.

Additional wayfinding systems and safety equipment in the tunnel includes assistance buttons, fire extinguishers and emergency phones. Assistance buttons are placed on the right wall in both tubes and are marked with the Swedish word for assistance. When a button is pressed a signal is transmitted to the traffic information central (TIC) that can dispatch a road assistance vehicle. The motorist can be informed that help is on the way using the tunnels public announcement system, but he or she can not speak to anyone at TIC. Assistance buttons are mainly used in case of a breakdown and are not directly related to fire emergencies. Fire extinguishers and emergency phones are placed in traverse tunnels. Their location is indicated by signs above emergency exits (see Fig. 2 and Fig. 3).

2.3. Instruments

2.3.1. Video cameras

The experiment was recorded by 15 video cameras, which provided complete coverage of exits, vehicles and participants. Fig. 5 shows the location of the 12 cameras closest to the simulated accident. Video recordings were used to determine the time when three distinct events occurred, namely when participants stopped their vehicle, began to open the vehicle door and reached an emergency exit. All times were measured relative to the time when the first participant, i.e. participant number one, stopped his vehicle.

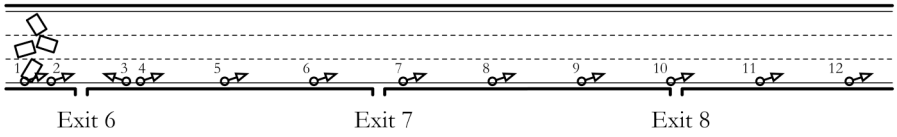

Fig. 5. The location of the 12 cameras closest to the simulated accident (The distance between emergency exits is 100 m.)

2.3.2. Questionnaires

The participants completed two questionnaires. The first questionnaire, which the participants were asked to fill out while waiting in their vehicles to enter the tunnel, contained an instruction sheet and 12 items measuring the basic emotional process before the evacuation. The second questionnaire was answered by participants as soon as they had entered the opposite tunnel tube. This questionnaire included, at the first page, the items measuring the basic emotional process after evacuation. The subsequent 10 pages contained questions relating to the evacuation, wayfinding systems, safety equipment and fire alarm.

The emotional state was assessed in terms of four basic emotional qualities each measured by three four-grade rating scales, namely activation (alert/sleepy), orientation (interested/bored), evaluation (happy/sad) and control (confident/hesitant) according to Küller [16]. This instrument has previously been successfully applied in the field of environmental perception and it has proved reliable in studies of people's response to the built environment [17,23].

Other items in the second questionnaire analysed for the present objectives were:

(a) Four questions that required the participants to indicate if they had noticed specific wayfinding systems or safety equipment, namely wall signs, assistance buttons, fire extinguishers and flashing lights at emergency exits.
(b) One question about associations with the flashing lights in terms of welcoming, frightening, insecurity, exit, do not come this way and other (please state).
(c) One question about the reasons for leaving the vehicle, chosen from a list of 10 pre-defined alternatives (see Table 1).
(d) Two items relating to the audibility of the pre-recorded alarm in the vehicle and in the tunnel, rated on a five-grade scale (see Table 2).

In addition, information about previous experience of road tunnels and emergencies as well as demographics was analysed.

Table 1. Participants' answers to the question relating to their reasons for leaving the vehicle, i.e., What made you leave your vehicle?

Stated reason	Participants		
	1 to 19	20 to 29	All
Became worried	1	0	1
Saw others evacuating	15	4	19
Heard pre-recorded alarm	1	9	10
Saw information signs	1	7	8
Saw evacuation exits	5	3	8
Saw a fire	0	0	0
Someone told me to	1	0	1
Thought is was the right thing to do	6	1	7
Other reasons	5	1	6
Total number of participants	19	10	29

Table 2. Participants' estimation of the audibility of the pre-recorded alarm in the tunnel and the vehicle according to a five-grade scale

Audibility	Number of participants	
	In the vehicle	In the tunnel
Very clear	0	2
Moderately clear	2	6
Moderately unclear	4	5
Very unclear	3	1
Did not hear the pre-recorded alarm	1	0
∑:	10	14

2.3.3. Interviews

Four participants were interviewed after they had completed the second questionnaire. Four interviewers performed the interviews based on a checklist with 24 pre-defined open-ended questions relating to the evacuation. More specifically, questions focused on initial cues, interpretation of the evacuation, actions, wayfinding systems, safety equipment, fire alarm and previous experience. The participants' evacuation paths were followed during the interview, which meant that the interview started in the participant's vehicle and ended in the opposite tunnel tube. Along the path, questions were asked at different pre-determined locations. All interviews were documented by the interviewers and recorded by means of recording devices.

2.3.4. Focus group sessions

In addition to the interviews, all participants took part in one of three focus group sessions, in which different aspects of the evacuation were discussed. These discussions were based on a checklist focusing on the same themes as

the individual interviews. Discussions were lead by three focus group leaders and took place in traverse tunnels. The three sessions, which were documented by note takers and recorded by means of recording devices, lasted approximately 20 min.

2.4. Procedure

2.4.1. Preparations

A project group consisting of employees at Lund University and the company MTO Psychology planned the experiment. Planning included not only specification of the accident scenario, but also development of questionnaires and checklists for the interviews and focus group sessions.

Possible accident scenarios were also discussed with experts in the field, which included employees at SRA. However, care was taken not to spread information about the evacuation and only a small group of SRA employees were informed about the true purpose of the study. Information given to potential participants during the recruitment process was also limited in order not to reveal the exact details of the experiment. Potential participants were only told that the study was focused on driving behaviour and technical installations. The evening before the experiment the tunnel was closed and cameras were installed. Parts of the experiment were also practiced and smoke machines were tested.

2.4.2. The experiment

On the evening of November 22, 2006, participants gathered for a meeting at the SRA headquarters in Göteborg. At the meeting participants were told that they were taking part in a study about driving behaviour and technical installations, e.g., variable speed limit signs and traffic information signs, and were shown a route around Göteborg that they were instructed to follow. Observations from the meeting suggest that many focused on a difficult passage at another tunnel, namely at the Lundby tunnel. Participants were also informed that participation was voluntary, about safety precautions and what measures to take if they did not want to continue.

After the meeting, participants went to their cars and attached numbers to their vehicle and clothes. They then drove together to the Göta tunnel, which had been closed, and parked in front of the entrance. While participants were waiting in their cars to enter the tunnel they completed the first questionnaire.

At 22.25 participants drove into the tunnel. The speed limit was restricted to 50 km/h and only the middle lane was open, which forced participants to form a single lane queue. At emergency exit number six, participants were hindered

by a simulated accident consisting of four cars and artificial smoke. Two minutes and thirty seconds after the first participant had stopped, the fire alarm, i.e., the information signs and the pre-recorded alarm, was activated and the green flashing lights at emergency exits six and eight were started.

When participants had exited to the other tunnel tube they were met by assistants who informed them that the evacuation was part of the experiment and asked them to fill out the second questionnaire. In addition, four participants were selected for interviews based on the order at emergency exits. Three of the interviewees were among the first to arrive at an emergency exit, namely participants 2, 10 and 23, and the forth, namely participant 29, among the last. Finally, focus group sessions were performed before the experiment was terminated and participants were allowed to leave.

2.4.3. Analysis of data

The video recordings were examined to determine the time when the participants stopped their vehicle, began to open the vehicle door and reached an emergency exit. Data from questionnaires were statistically analysed in SPSS 14.0 [24]. All data were analysed by frequency analysis. In order to identify differences in emotional state between subjects the data were treated by one-way ANOVA and ANCOVA. A significance level of five percent was used in all statistical tests.

All interviews and focus group sessions were subject to content analysis. In these analysis statements relating to green flashing lights, the pre-recorded alarm, information signs, social influence and associations were focused upon and summarised under related headings. Transcriptions were made of all interviews and of relevant sections of focus group sessions.

3. RESULTS

The results are presented in subsequent sections. Some sections include quotes from focus group sessions. These quotes have been translated from Swedish by the authors. All quotes are indented and in some cases include clarifications, which are indicated by parenthesis.

3.1. Arrival at the accident

The first participant started to reduce speed approximately 60 m in front of the accident, but did not stop until he was less than the length of one car from the accident. As the other participants arrived they stopped fairly close to the car in front. The distance between cars was seldom more than half the length of one car. However, one exception was participant number five who stopped

further behind the car in front. This participant also turned on both flashing direction indicators when passing emergency exit number seven. As can be seen in Fig. 6, which shows the approximate location of the vehicles in the tunnel, the queue extended from the accident to midway between emergency exits eight and nine. The times at which participants stopped their vehicles are given in Fig. 7, which shows that the last car came to a halt approximately 3 min after the first car had stopped.

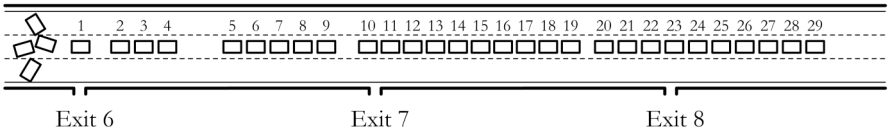

Fig. 6. The location of vehicles in the tunnel (The distance between emergency exits is 100 m.)

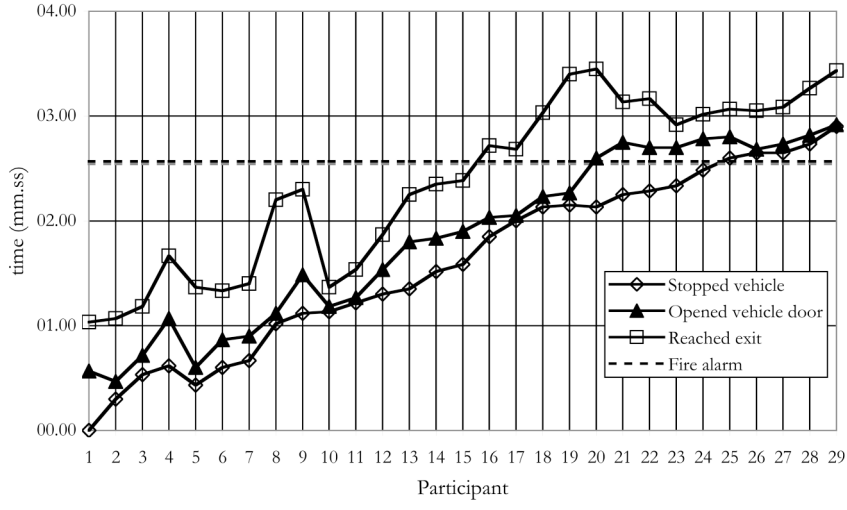

Fig. 7. The time at which the participants stopped their vehicles, opened the vehicle door and reached an emergency exit.

3.2. Time to respond and exit choice

Participants located in the front of the queue opened the door of their vehicle and began to move towards exits before the alarm was activated (see Fig. 7). Nineteen participants had already left their vehicle and 15 of them had also reached an emergency exit at the time of the alarm. This meant that only 14 participants could see information signs and green flashing lights or hear the

pre-recorded alarm whilst evacuating the tunnel tube. In addition, 10 of those 14 participants were still sitting in their vehicles when the alarm was activated, namely participants 20–29.

In Fig. 7, it can be seen that everyone responded swiftly and without significant delay. The time between stopping and beginning to open the vehicle door was between 1 and 35 s. All participants had reached an emergency exit within 1 min and 20 s of stopping their vehicle.

Participants used the closest emergency exit with few exceptions and the wall signs pointing towards the tunnel entrance were not necessarily followed (see Fig. 8). Ten of the 21 participants who reported noticing the signs used an emergency exit located in front of them, i.e., moved in the direction towards the tunnel exit.

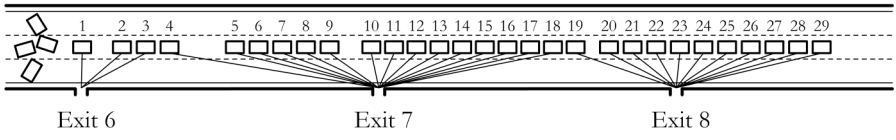

Fig. 8. Emergency exits used by participants.

3.3. Factors influencing response and exit choice

From the items relating to participants' reasons for leaving the vehicle, i.e., for responding, it can be seen that *Saw others evacuating* was a common reply for participants 1–19, who left their vehicles before the alarm was activated (see Table 1). The alternatives heard pre-recorded alarm and saw information signs was more common for participants 20–29, who were still sitting in their vehicle at the time of the alarm. In total, 19 of the 29 participants reported that they were influenced by others when deciding to leave their vehicle.

The fact that social influence was important is also evident from the focus group sessions. Many mentioned that they had been influenced by others and their actions when deciding to leave their vehicle. One example is the answer given by a participant when asked about the reasons for leaving his vehicle:

Well, others exited

A second participant also added the following statement:

I came in very late, so I only saw that everyone walked in. That was the only reason.

Yet another example is the statement given by a third person who took part in the same focus group sessions:

> *I did not think at all. I only followed the stream (of people) and did the same thing as everyone else.*

Some participants also mentioned that they based their exit choice on the actions of others. One person, who explained his exit choice, said:

> *The first thought was probably which way is closest, so to say entrance or exit. And then you saw others walking towards the exit and you followed (them).*

Another participant explained his exit choice by saying:

> *People before me went in that way, so I just followed.*

3.4. Perception of technical installations

3.4.1. Pre-recorded alarm

The answers to the items concerning the audibility of the pre-recorded alarm, i.e., how clearly the message could be heard, both in the vehicle and the tunnel show that the message was difficult to perceive in the vehicle, but somewhat easier to make out in the tunnel (see Table 2). As mentioned previously, only 14 participants were in the tunnel when the alarm was activated and only 10 of them were still inside their vehicle (see Fig. 7).

Interviews and focus group sessions also confirm that information contained in the pre-recorded alarm was difficult to perceive. One interviewee said that he was not able to understand the message while inside his vehicle and that it sounded as if someone was mumbling. He also added that the message was hard to make out outside the vehicle. Another interviewee gave a similar account and added that echoes made it difficult to understand what was said. Similar comments were frequent in the focus group sessions. One example is the answer given by a participant when asked if the volume of the message was too low:

> *It was a bit unclear as well. She repeated it several times and finally you started to get the context.*

Although the information contained in the pre-recorded alarm was difficult to perceive, the mere existence of an acoustic signal was appreciated. It was pointed out in one of the focus group sessions that some type of signal was

positive, since it made people respond when sitting in their vehicles. The fact that nine of ten participants mentioned the pre-recorded alarm as a factor influencing them to leave their vehicle confirms this, see participants 20–29 in Table 1.

3.4.2. Information signs

When the information signs were activated, i.e., at the time of the alarm, only 14 participants were in the tunnel. Two interviewees mentioned seeing the sign and one said it had been a factor influencing him to leave the vehicle. Answers from the second questionnaire confirm that the sign was deemed important for the decision to leave the vehicle, see participant 20–29 in Table 1. This is also confirmed by statements from focus group sessions. However, some participants who left their vehicles after the alarm was activated mentioned that they had not seen the signs before leaving their vehicle.

3.4.3. Green flashing light at emergency exits

A green flashing light was placed underneath the exit sign at exits six and eight. Participants using exit six had entered the traverse tunnel long before the light was activated, but participants who used exit eight had not begun to open the door of their vehicle (see Fig. 7). Only three of the 10 participants who used exit eight acknowledged that they had seen any green flashing lights in the second questionnaire, namely participants 19, 23 and 28. When asked about associations with the flashing lights one selected welcoming and two exit from a list with six pre-defined alternatives.

Participant number 23, who was the first person to reach exit eight, was interviewed. In the interview he mentioned that the flashing light was good since it made you see the exit quickly. He also pointed out that the light focused ones attention to the exit sign, which pointed towards the emergency exit. One participant also mentioned in a focus group sessions that he had chosen exit eight because of the green flashing light.

A peculiar result is that three participants who used exit eight and did not remember seeing any green flashing light suggested flashing lights as a way of getting peoples attention. One example of this is the answer given by a participant when asked if any information was missing:

> *Possibly something that attracts attention even more, such as lights along the walls that flashed intensively, so that you understood that something was happening.*

A second participant then added:

> *If nothing else that the evacuation stations (emergency exits) here were flashing with the colour green or something. A positive colour.*

In another focus group session one person gave the following answer to a question relating to the adequacy of the provided information during evacuation:

> *I think the exits should be surrounded by some type of red flashing lights or something.*

The three participants who suggested flashing lights did not remember seeing any green flashing light. However, it was not possible to determine from video recordings if they had looked at the green flashing light at exit eight.

3.4.4. Other wayfinding systems and safety equipment

In the second questionnaire participants stated whether they had noticed additional wayfinding systems or safety equipment, i.e., wall signs, assistance buttons and fire extinguishers. As mentioned previously 21 of the 29 participants reported that they had seen wall signs during evacuation. In addition, assistance buttons were noticed by four and fire extinguishers by three persons. Twenty-three participants had noticed at least one system or one piece of equipment.

3.5. Previous knowledge of road safety and evacuation procedures

Interviews and focus group sessions show that many participants were aware of dangers involving traffic. More specifically, some participants mentioned that they had been careful when opening the door to the opposite tunnel tube. One example is the explanation given by an interviewee:

> *So I carefully opened the door to the other side (to the opposite tunnel tube) because I thought there would be traffic and did not want to step straight out (into the road).*

Although many participants were aware of dangers involving traffic they were not necessarily familiar with evacuation procedures. Three participants mentioned in focus group sessions that they thought there would be stairs or elevators to the surface, which was clearly not the case for the Göta tunnel. In the second questionnaire participants were asked if they knew about systems aiding evacuation in the Göta tunnel before the experiment. Five participants mentioned that they were familiar with most systems, 18 that they had some

understanding of parts of the systems and five that they were not familiar with any systems.

Participants were asked in the second questionnaire if and how often they had driven thorough a tunnel in the last month (see Table 3). Since participants worked in Göteborg, where there are many tunnels, most had driven through a tunnel at least once a week. Participants were also asked if they had any particular experience relating to fire and tunnels (see Table 4). Most participants had participated in fire drills and also had practiced extinguishing fires.

Table 3. Participants' estimations of how frequently they had used road tunnels in the last month

Frequency of tunnel use	Number of participants
Every day	11
Several times per week	5
Once a week	6
More seldom than once a week or never	6
Total number of participants	29

Table 4. Participants' previous experience of fire and tunnels

Type of previous experience	Number of participants
Evacuation from building, tunnel, ship or similar	10
Participated in fire drill	21
Practiced extinguishing fires	21
Walked long distance in a road tunnel	15
Walked long distance in a rail tunnel	1
Serious incident/accident	2
Total number of participants	29

3.6. Emotional state

The first assessment of the participants' emotional state showed that before evacuation as a group they were fairly activated, oriented towards the task, evaluated the situation in positive terms, and felt control. This indicates that the participants were aroused, but concentrated and in a good mood while they were waiting in their cars to enter the tunnel (see Table 5). The statistical analyses revealed that the emotional state did not significantly differ when participants answered the questionnaire after the evacuation, i.e., they were still aroused, concentrated and in a good mood.

Table 5. The participants' mean values and standard deviation for the four dimensions of the basic emotional process before the experiment

Dimension of the basic emotional process	Mean	SD
Activation	2.91	0.48
Orientation	3.15	0.54
Evaluation	3.45	0.39
Control	3.05	0.55

The participants' emotional state was not, either before or after the evacuation, significantly related to evacuation time and choice of emergency exit. Some differences were, however, identified between participants with different experience in terms of what environmental features they had noticed during the evacuation. The features that were identical during the complete experiment and that would have been possible for all the participants to attend to were the additional wayfinding systems and safety equipment (see Section 3.4). Those who had noticed at least one of these technical installations reported a lower level of activation both before and after the evacuation than those who had not. Participants who had noticed the additional wayfinding systems and safety equipment also seemed to be less focused, reporting a lower level of orientation than did those who had not noticed the information. These results remained stable even when the participants' age, gender and previous experiences of evacuation situations and road tunnels were controlled for (ANCOVA). No significant differences could be identified for the participants' levels of evaluation and control. The statistical results are given in Table 6.

Table 6. Differences in the basic emotional process between participants who did and who did not notice the additional wayfinding systems and safety equipment

	Activation			
	Before evacuation		After evacuation	
	Noticed	Not noticed	Noticed	Not Noticed
Mean	2.84	3.44	2.81	3.33
ANOVA	F(1, 28)=7.13, p=.013		F(1, 28)=6.60, p=.016	
	Orientation			
	Before evacuation		After evacuation	
	Noticed	Not noticed	Noticed	Not Noticed
Mean	3.12	3.78	3.05	3.50
ANOVA	tendency, p=.07		F(1, 28)=5.73, p=.024	

In order to investigate the impact of social influence on emotional state the participants were divided into two groups, namely those who reported that they had been influenced by others before they decided to leave their vehicle

(19 persons) and those who did not say that they had been influenced (10 persons). Participants who said they had been influenced reported a significantly lower level of activation after the evacuation (see Table 7). Similarly, a comparison between participants who had taken the lead when walking through emergency exits and those who had merely followed others revealed that participants who followed reported a lower activation level (see Table 7). Leading participants consisted of the first two who reached emergency exit six, the first three who reached emergency exit seven and the first three who reached emergency exit eight. Neither of the results reported above can be attributed to differences in participants' gender, age or previous experiences of evacuation and road tunnels. No impact of social influence could be identified for the participants' levels of orientation, evaluation or control.

Table 7. Differences in the participants' basic emotional process due to social influence during the evacuation

	Activation			
	After evacuation		After evacuation	
	Not influenced	Influenced	Lead	Follow
Mean	3.20	2.77	3.25	2.79
ANOVA	F(1, 28)=5.73, p=.024		F(1, 28)=6.05, p=.021	

3.7. Perception of the evacuation

Participants were asked about their associations when exposed to the simulated emergency. This question was included both in interviews and focus group sessions. The prevailing association was that the fire emergency was in fact a drill or exercise. Some participants added that although they had not expected that they were going to evacuate one of the tunnels they were expecting something out of the ordinary to occur. One example is a participant who stated in his questionnaire that he was not prepared for the situation that occurred. Another participant mentioned in one of the focus group sessions that he knew it was a drill, but that it was still comforting to get a confirmation of this.

4. DISCUSSION

The present study provides valuable information regarding motorists' responses in terms of perception of technical installations, behaviour and emotional state in the event of a fire emergency in a road tunnel. One important feature of the research is that multiple sources of evidence, namely observations, questionnaires, interviews and focus group sessions were used in a triangulating fashion. In accordance with the HEI model the participants'

responses were studied using a holistic approach that included both physical and social environmental factors and also considered some of the participants' individual characteristics. The study is also special since human behaviour was studied for a realistic fire scenario in a tunnel environment. Due to ethical reasons an unannounced experiment with ordinary tunnel users is not viable, but the experiment in the Göta tunnel was designed to be as realistic as possible.

All the participants evacuated in the experiment and everyone had begun to open the vehicle door within 35 s. In comparison with previous studies of real fire emergencies in tunnels [1,2] this seems to be an unexpectedly fast and homogenous response to the situation. It is probable that the participants were aware that something was going to happen, although they did not expect an evacuation. The assessment of the participants' emotional state before they entered the tunnel indicates that they were aroused and oriented towards the task, i.e., the swift response may partly be explained by the fact that they were prepared to act. Although no information about the evacuation was revealed participants were still expecting something out of the ordinary. The participants' expectations may have resulted in increased alertness compared to tunnel users in general. It is also possible that participants were more willing to leave their vehicles behind than they would have been in a real emergency. The increased alertness and the willingness to leave their vehicles are important factors that likely led to much shorter response times in the experiment that can be expected in a real fire emergency in a road tunnel. In addition, the expectations of the participants may also explain why many of them interpreted the experiment as a drill.

An interesting result is that participants frequently used the closest emergency exit. This supports findings regarding exit choice from experiments in the Benelux tunnel [19]. Even more interesting is that people used the closest exit even if they observed wall signs pointing in the opposite direction. However, it is not clear from the study whether participants observed the signs before or after they had started to move towards an exit. If a sign is observed after movement is commenced the person has most likely already made up their mind and a sign may not provide sufficient incentive to change that decision.

Emotional state did not directly influence the choice of exit, but might have done so in an indirect way. Those who initially reported a higher level of arousal tended to miss the more peripheral evacuation information, including wall signs pointing in the direction of the tunnel entrance. Since many of the participants associated the evacuation with a drill or exercise they most likely experienced less activation and higher control than what might be the case in a

real emergency situation, i.e., the proportion of people who will miss the information might be greater for a real emergency.

An evacuation message may be quite difficult to perceive in a road tunnel, but an acoustic signal can have a positive effect since it alerts motorists and makes them look for additional information. Results suggest that information contained in the pre-recorded alarm was difficult to make out. However, an acoustic signal is considered important since it alerts motorists. Even though few could make out the message in their vehicle the alarm seemed to indicate to participants that something out of the ordinary was occurring. This may have led them to search for additional information, e.g., information signs and the evacuation behaviour of others, which in turn may have influenced them to respond. Information signs are one way to convey concise and precise information to motorists about a fire emergency. Results indicate that the signs played an important role in the experiment and influenced participants to leave their vehicles. However, a disadvantage is that signs may be difficult to observe from inside a car.

The results suggest that green flashing lights at emergency exits, if noticed by motorists, influence their choice of exit and are considered important. Although the lights used in the experiment were regarded as easily distinguishable features by the authors, few participants acknowledged seeing any green flashing lights at exits. Surprisingly, some participants who did not recall the light at exit eight suggested similar systems in focus group sessions. It is unexpected that so few recalled the green flashing light at exit eight. One possible explanation is that the light was not seen as an outstanding feature of the emergency exit, but as an integrated part. The participants may have seen the exit, including the flashing light, and stored the information temporarily in working memory. However, since the light was not seen as an outstanding feature the information was not stored in long-term memory and could hence not be recalled later [26]. However, based on the results it was not possible to neither confirm nor dismiss this theory.

The results show that social influence is particularly important during evacuation in road tunnels, i.e., that people are influenced by the behaviour of others. This confirms conclusions from evacuation experiments in the Benelux tunnel [19]. In the present study social influence could be divided into two distinct types. The first type involves the decision to leave the vehicle. Based on the results it is clear that the evacuation behaviour of others is an important cue that influences people to respond. If someone starts to evacuate he or she will be observed by others and influence them to evacuate. This trend was particularly clear when additional cues were limited, i.e., when there was no alarm. Previous research has shown that social influence decreases when the

information becomes clearer [25], which supports the results from the Göta tunnel experiment. The second type of social influence involves the choice of exit. Results indicate that people are influenced by the exit choice made by other motorists.

The assessments of emotional state further suggest that social influence may have had a stress-reducing effect in the experiment. Participants who reported that they had been influenced by the behaviour of others in their decision to leave their vehicle and who followed other participants through an exit had a lower level of activation/arousal after evacuation. This implies that those who, for some reason, could not take advantage of other people's behaviour did not relax as quickly when informed that the emergency was part of the experiment. It should be added that it was not investigated if there were any other differences, e.g., demographic or cognitive factors, between those participants who reported that they had been influenced by others and those who did not. Future studies could therefore explore the influence of individual demographic and cognitive factors on the response of motorists in the event of fires in road tunnels. In order to fully understand how motorists respond it might be fruitful to consider individual characteristics, e.g., personality traits, in relation to group formation processes during the evacuation process.

One limitation of the study is that the participants were either SRA employees or consultants working for SRA, which also influenced the age and gender distribution of the studied population. The fact that participants were connected to SRA meant that they were likely more knowledgeable about road safety issues than the general public. The participants' background has already been discussed in relation to the swift response. Their background may also explain why several persons were aware of dangers involving traffic in the opposite tunnel tube and were very careful during evacuation. However, some thought that there would be stairs or elevators leading from the traverse tunnels to ground level, which suggests that knowledge about road safety, in general, does not necessarily lead to increased understanding of evacuation procedures in tunnels. In spite of the limitations of the experiment, it is believed that the results relating to human behaviour and the perception of technical installations are relevant for real fire emergencies. More specifically, this type of realistic experiment can identify potentially problems and reveal how people are likely to behave in the event of fire in a road tunnel. For example, the present study has shown that a message is difficult to make out, but also that some type of acoustic signal is preferable because it alerts motorists and makes them look for additional information.

The fact that emotional state for practical and ethical reasons was assessed after the evacuation, i.e., when participants had been informed that the

evacuation had been part of an experiment, has certainly influenced their reply. Being told that the situation was not a real emergency most likely decreased the participants' activation and increased their evaluation and perceived control. This implies that the participants probably were in a more positive mood and less aroused after the evacuation than people would have been in a real emergency. The measures of the basic emotional process provide valuable information about the interaction between people's emotional state and their response to the emergency situation. The actual levels of the participants' four emotional dimensions may deviate from what their emotional state would have been in a real emergency situation. Still, the differences in emotional response between people with different evacuation behaviour may be generalized. Considering that people with a high level of arousal tended to miss the additional wayfinding systems and safety equipment it seems most important to evaluate the design of various technical installations among the public for safe but stressful conditions before they can be relied upon.

Many valuable conclusions can be drawn from the study in spite of differences between the experiment and a real tunnel fire. The study has provided important insights into motorists' behaviour, emotional response and perception of technical installations. However, participants most likely evacuated more willingly and responded more swiftly than what can be expected for a real tunnel fire.

5. CONCLUSIONS

The study suggests that social influence plays an important role both for the decision to leave the vehicle and the choice of exit during evacuation. Since people are influenced by others it is imperative that someone begins to evacuate. Results indicate that evacuation messages may be difficult to make out in a road tunnel, but that an acoustic signal is preferable since it alerts motorists and makes them look for additional information. Information signs are a good way to deliver concise and precise information about an emergency. Green flashing lights may also be important, but results suggest that motorist do not always consciously notice lights at emergency exits. The study of emotional state indicates that arousal level influences the amount of information that is noticed by motorists. This suggests that technical installations, e.g., wayfinding systems, should be tested under stressful conditions before they can be relied upon in a real tunnel fire.

6. ETHICAL CONSIDERATIONS

According to the Swedish ethics act [27] all research that involves procedures that may be psychologically invasive to the participants must be subject to a review by a regional ethics board. The present study was reviewed and consequently approved [28]. The important ethical issues discussed below were identified and addressed within the project.

6.1. Preparation and precautions

A number of precautions were taken to avoid both psychological and physical injury in the experiment. The risk of psychological injury was minimised by preventing individuals who received a high score for both anxiety and depression according to the HAD questionnaire [22] from taking part. In addition, one of the researchers was responsible for taking care of participants if they displayed signs of acute anxiety during the experiment.

Clear safety instructions were given to participants and the speed limit in the tunnel was restricted to 50 km/h to minimise the risk of physical injury. The opposite tunnel tube was closed for traffic before the experiment was initiated to avoid accidents when people exited the traverse tunnels. In addition, the rescue service was informed and on constant stand-by to enable prompt response.

One important ethical aspect of the experiment was the violation of informed consent, i.e., the requirement that participants should be properly informed about the experiment to enable them to make an enlightened decision about taking part. The participants received information beforehand, but this information was slightly misleading to create an element of surprise. This procedure is a violation of informed consent, which is required by the Swedish ethics act [27], since participants did not receive information about the true purpose of the study. However, the slight deception was deemed necessary in order to create a more realistic experiment and to improve the validity of the results. The violation of informed consent was also approved by the ethics board [28].

6.2. Debriefing and dehoaxing

Debriefing of participants was performed in the focus group sessions to ascertain that no one left the experiment with feelings of anxiety or stress. Proper dehoaxing was also performed by informing participants about the true purpose of the study and explaining why the slight deception was necessary. This procedure, which was described in the ethics application, was reviewed and approved by the ethics board [28].

ACKNOWLEDGEMENTS

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Paper IV

INFLUENCING EXIT CHOICE IN THE EVENT OF A FIRE EVACUATION

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ABSTRACT

Unannounced evacuations were performed in both an office building and a cinema theatre in order to investigate if green flashing lights at exits can influence exit choice. Also studied was how the exits were perceived and the results were interpreted using the theory of affordances. The results indicate that green flashing lights can be used to influence exit choice in the event of a fire emergency. However, the effectiveness of the system seems to depend on the setting, e.g., the type of building. The results suggest that green flashing lights at an emergency exit, if used in an appropriate setting, makes the exit stand out and encourages people to use it.

KEYWORDS

Human behaviour, egress, emergency evacuation, exit choice, green flashing lights, theory of affordances.

INTRODUCTION

In the event of a fire emergency it is often essential that people use emergency exits in order to reach a safe place quickly. However, fire accidents and evacuation experiments have shown that people often use familiar exits instead of more unfamiliar emergency exits [1,2,3]. A familiar exit can be for example the entrance of a building or the ordinary exit.

One possible way to influence exit choice is to install way-guidance systems. Many different types of systems for directing people have been suggested for both smoke logged [4,5,6,7] and clear fire conditions [8,9]. A way-guidance system that has been evaluated in many studies is flashing lights at exits [7,8,9]. However, previous studies have been either questionnaire studies or experiments with informed participants, i.e., participants who knew that they were taking part in an experiment. Although these studies have provided valuable information about the system, such as the influence of different colours of the flashing lights [9], they have inherent limitations. It is therefore

relevant to test flashing lights at exits in realistic scenarios (in experiments with participants who have not been informed about the evacuation beforehand). These types of experiments should ideally provide a realistic estimate of the effectiveness of the system.

Previous research has suggested that the design of an exit can influence how often it is used. One example is an experiment performed at an IKEA store by Frantzich [3]. In Frantzich's experiment some emergency exits were used more frequently than others because they were placed along the extension of the walking path as opposed to at a ninety degree angle. The example illustrates that the design, in this case the location, is an important factor that should not be ignored.

A theory that is useful for analyzing exit design is the theory of affordances introduced by Gibson [10]. Gibson used the theory as a way of explaining how individuals perceive things they see. An affordance is what the object offers the individual in relation to the fulfilment of their goal. If a person's goal is to get from A to B an asphalt road affords both running and walking, but a swamp barely affords walking. One goal (of possibly many) in the event of a fire emergency is to escape. Emergency exits should therefore provide affordances that support escape, e.g., should be clearly marked, distinguishable from the surrounding, not locked, easy to open, etc.

The theory of affordances has been applied to a number of areas that range from perception of climbing routes [11] to human-computer interaction design [12]. Over the years the theory has also been expanded to fit different disciplines. One example is the four types of affordances introduced by Hartson [12] for interaction design. Hartson divides affordances into sensory, cognitive, physical, and functional based on how they support the user. Sensory affordances support the user in sensing, e.g., seeing, something. An example of a feature that provides sensory affordance can be large letters that make a sign easy to read. Cognitive affordance support understanding about the observed object, e.g., how it is used or what it is used for. If an opening device of an emergency exit is complicated it may be difficult to understand how it should be used, i.e., the device does not offer the potential user sufficient cognitive affordance. Physical affordance supports physically performing something, e.g., opening or closing a door. An example of a feature that provides physical affordance is that the handle of an exit door is placed at an appropriate height. Finally, functional affordance helps the user to achieve their goal, i.e., to accomplish the task they have set out to perform. If a person wants to escape as quickly as possible a fire extinguisher although it is easy to see, understand, and operate, would not offer functional affordance. However, fire extinguishers fill an important function and would have provided

appropriate functional affordance if the person's main goal was to extinguish the fire.

In order to illustrate the theory of affordances it is useful to consider a simple exit design such as the left exit in Fig. 1. There are many features of the exit that provide different types of affordances in the event of a fire emergency. Since the door is a different colour than the background it is clearly distinguishable and easy to identify. The contrast between the door and the wall can therefore be seen as a sensory affordance. Another sensory affordance is provided by the emergency exit sign, which stands out on the white wall. Given that people are familiar with the meaning of the sign it also provides cognitive affordance since it informs potential users that the door can be used to leave the building in the event of an emergency. This, however, requires that people are familiar with the meaning of the sign. Physical affordance supports performing something and is therefore difficult to derive from a picture. However, the door handle of the exit looks uncomplicated and is probably easy to use. The simple handle may therefore provide physical affordance by making the door easy to open. The exit may also provide functional affordance for a person who wants to escape given that they see, understand and can use it.

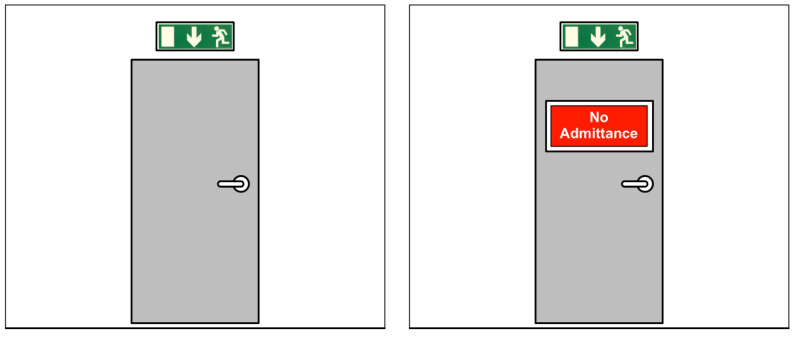

Fig. 1. An emergency exit (left) and an emergency exit with a *No Admittance* sign (right).

Another example of a common exit design is illustrated by the right exit in Fig. 1. The only difference between the two exits in the figure is that the right exit is also marked with a *No Admittance* sign since it is not supposed to be used in normal situations but only for emergency purposes. However, this simple modification may potentially change people's perception of the exit. The two signs provide conflicting cognitive affordances in the event of an emergency, namely knowledge that the exit should be used and that it should not be used.

This conflict may cause uncertainty and possibly inhibit people from using the exit to escape.

Another type of conflict has been discussed by Hartson [12] who focuses mainly on situation when the cognitive affordance is not in agreement with the physical affordance provided by an object. One example is a pull handle on a door that can only be pushed open. In this case the handle provides false cognitive affordance that misinforms or misleads the user according to Hartson [12].

In this study unannounced evacuations were performed in order to study if flashing green lights can influence exit choice for realistic settings. Experiments were performed in both an office building and a cinema theatre. It was also investigated how the flashing lights influence people's perception of the exit and the results were interpreted using the theory of affordances.

EVACUATION OF AN OFFICE BUILDING

An unannounced evacuation of an office building at AstraZeneca pharmaceutical company in Mölndal, Sweden, was performed at 10.30 on 19 May 2006. Green flashing lights at exits were used on some floors to study if the lights could influence people's choice of exit. Most participants in the experiment were familiar with the building since it was their work place.

Participants

People who took part in the evacuation consisted of employees at AstraZeneca who were in the building when the fire alarm was activated and it is estimated that 400 people took part. No information about the evacuation had been revealed beforehand. The fire alarm was activated in the entire building, but only four floors were included in the study. People who were located on other floors were hence excluded from the analysis even though they took part in the evacuation.

Based on a comparison between the video films and the questionnaires it is estimated that approximately 150 participants were on the included floors, namely floors three, four, six and seven, when the alarm was activated. However, only 98 of the participants on the four included floors filled out a questionnaire. Of these 98 people 72 were women, 25 men and one did not state gender. The average age was 45 years with a standard deviation of 10 years (five participants did not state their age in the questionnaire). Most participants worked in the building, but 26 were only attending meetings. Those participants who worked in the building had worked there between 1

month and 11 years (average of 4 years). Only 40 participants stated that they had taken part in a fire drill in the building before.

The office building

The office building has ten floors, comprising the basement, the ground floor and floors one to eight, see Fig. 2. The main entrance faces north and is located on the ground floor. In the centre of the building there is a central staircase and four elevators, which are often used to enter and exit the building. There are also two additional elevators and a staircase in the south part of the building, which are sometimes used for getting to and from the company restaurant. In addition, there are two spiral staircases called the west and east staircase that are evacuation exits from all floors to ground level. The spiral staircases are seldom used, but may sometimes be used to move between floors. All staircases are protected means of escape. Some floors are also connected to adjacent buildings to the west and east. All doors are locked and can only be opened from the outside with magnetic cards. From the inside the doors may be unlocked by pressing a button.

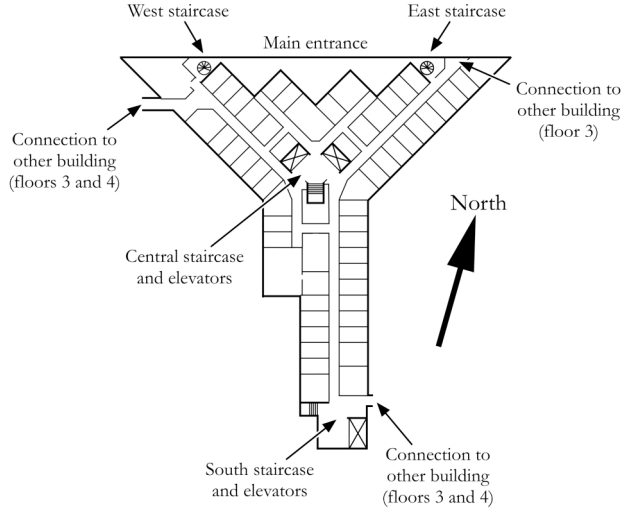

Fig. 2. A layout of the office building.

Most floors are similar and contain mainly office spaces and meeting rooms that are connected by a network of corridors. Two pairs of floors are especially similar with regards to both interior layout and number of exits, namely floors three and four and floors six and seven. In the event of an emergency it is possible to leave floors three and four using any of the four staircases as well

as connections to two other building, see Fig. 2. However, for floor three it is also possible to escape via a connection in the northeast corner of the building. For floors six and seven the only means of escape are the four staircases. Due to the similarities mentioned above only floors three, four, six and seven were included in the study.

Apparatus and materials

All evacuations were filmed with video cameras, which were placed on floors three, four, six and seven, i.e., the included floors. The cameras were put in paper bags and placed at the exits to the spiral staircases. All cameras were pointed towards the central staircase and the location provided a good overview of the sections of corridor marked in Fig. 3. In the video analysis of exit choice only those who at some point were located within the marked sections were included. This meant that participants who came from southern parts of the building and escaped directly to the central staircase were not included in the video analysis.

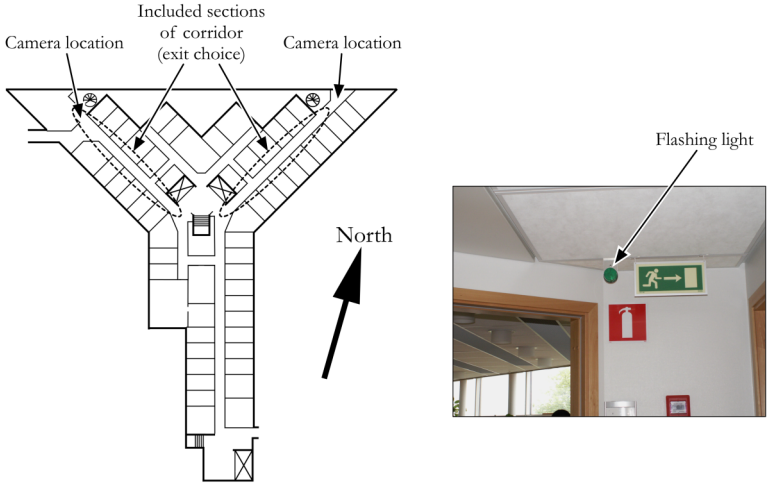

Fig. 3. The location of the cameras and the sections of corridor that were included in the analysis of exit choice (left) and a green flashing light at the west staircase (right).

The fire alarm in the building consists of bells that ring continuously until the alarm is reset. All bells are placed in the corridors. In the experiments the alarm was activated and terminated manually from the control panel on the ground floor.

One green flashing lights was used at each of the exits to the spiral staircases on floors three and seven. The light consisted of one green strobe light (xenon tube) with a diameter of 70 millimetres that was placed next to the emergency exit sign, see Fig. 3. During evacuation the lights flashed with a frequency of approximately one Hz (one flash per second). The lights were lit by manually flicking a switch when the alarm was activated. On the floors without flashing lights, i.e., floors four and six, there were still emergency exit sign that pointed towards the spiral staircases.

Everyone who evacuated to the gathering point in front of the main entrance was given a questionnaire. The questionnaire was divided into three parts that covered different aspects. In the first part participants were asked questions about the evacuation, namely what floor they were on, their initial location, which exit they chose, if they altered their choice of exit, what activities they were involved in prior to the alarm and what actions they undertook before starting to move towards an exit.

The second part of the questionnaire consisted of six questions, four about the exit that was chosen and two about exits that were not chosen to leave the floor. Questions were designed to elicit affordances associated with the exits. Care was taken during formulation to avoid implicitly suggesting important factors to participants. The questions were therefore general and aimed at probing encouraging and discouraging features of the exit design. All questions could be answered by ticking either No or Yes, where the Yes alternative required that participants specified what they meant.

The four questions about the exit that participants used to leave the floor were (translated from Swedish):

1. Did the exit stand out in any way?
2. Was the exit different compared to other exits?
3. Did the appearance of the exit encourage you to use it?
4. Did the appearance of the exit discourage you from using it?

The two questions about the exits that participants did not use to leave the floor were (translated from Swedish):

5. Did you notice anything special about other exits from the floor?
6. Did the appearance of other exits influence you not to use them?

In the final part of the questionnaire participants were asked background questions, namely questions relating to gender, age, time spent working in the building and experience of fire drills in the building.

Procedure

The cameras were started and placed on the four included floors a couple of minutes before the alarm was activated. At 10.30 the alarm was started manually from the control panel on the ground floor. When the bells began to ring the green flashing lights on floors three and seven were activated manually by observers. The observers then went to the gathering point in front of the main entrance and began to distribute questionnaires to people as they exited the building.

The alarm was turned off and the people were allowed to enter the building again when it had been searched by a security guard. On their way in through the main entrance they handed in the questionnaires. Since everyone did not necessarily assemble at the gathering point the questionnaires were also sent by email to everyone in the building a couple of days after the evacuation. People who had taken part in the evacuation, but had not handed in a questionnaire were urged to hand in the questionnaire sent by email.

Data analysis

The video films were analyzed to determine which exits were used to leave floors three, four, six and seven. Only people who were located within the marked sections in Fig. 3 at some point during the evacuation were included in the analysis of exit choice. This meant that those participants who came from other parts of the building and escaped directly to the central staircase were not included. Fischer's exact test [13] was used to investigate if the proportion of participants that used the spiral staircases differed between the floors with and the floors without green flashing lights, i.e, to test if the lights influenced people's exit choice. A significance level of 5% was used, i.e., $\alpha = 0.05$.

The questionnaires were sorted based on the floor location prior to the evacuation given by participants in the background questions. Only questionnaires from participants who were on floors three, four, six and seven when the fire alarm was activated were selected for further analysis. Participants' answers were used to obtain background information, e.g., age, gender, experience and use of exits for non-emergencies. An in-depth analysis of answers to the six questions about characteristics of exits was also performed. Participants who marked the Yes alternative on these questions were also asked to specify what they meant. The explanations given by participants were divided into categories according to Table 1.

The video films were also analyzed to get an idea of what actions participants undertook before they began to move towards an exit. Further information about the action of participants was obtained from the questionnaires.

Table 1. The categories that were used to classify answers to the six questions about exits.

Category	Description
Clearly marked	The exit was clearly marked as an emergency exit or was equipped with an emergency exit sign
Flashing light	There were flashing lights at the exit
Known exit	The exit was known, was the ordinary exit/entrance or was regularly used
Others used it	The exit was used by others (social influence)
Closest	Closest exit or short distance to exit
Big	The exit or stairs were big, wide or had a large capacity
Small	The exit or stairs were small, narrow or had a limited capacity
Crowded	Crowded or many people at the exit or in the staircase
Other	Other comments mentioned by less than three participants

EVACUATION OF A CINEMA THEATRE

Four unannounced evacuations of a cinema theatre in Lund were performed in March 2007. In two of the evacuations green flashing lights were placed at one of the two exits from the theatre in order to study if the lights could influence people's choice of exit. The participants in the experiments were not familiar with the building as they usually spend limited time in cinema theatres and furthermore have probably no experience with cinema theatre emergency evacuations.

Participants

Participants consisted of cinema visitors who had bought tickets for the shows. None of the visitors had received information about the evacuation beforehand and were hence unaware that the fire alarm was going to be activated. In one of the experiments a person exited the cinema theatre before the alarm was activated and was hence excluded from the study. The total number of participants was 49, namely 26 women and 23 men. The average age was 32 years and the standard deviation was 14 years according to the questionnaire. Participants were reimbursed with one cinema check, which allowed another visit to the cinema, after they had filled out the questionnaire.

The cinema theatre

The cinema theatre holds a maximum of 53 visitors, see Fig. 4. There are five rows in the theatre and along the left side there are stairs from the front to the back. This means that visitors can only exit a row from one end. In front of the first row of seats there is a handrail to prevent people from falling down from the first row to the area in front of the screen.

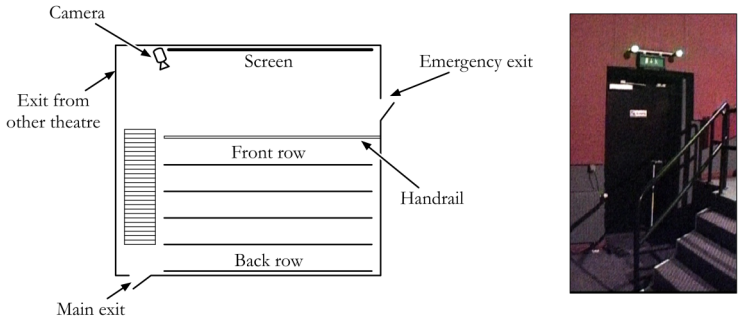

Fig. 4. A layout of the cinema theatre (left) and green flashing lights at the emergency exit (right).

Three doors connect the cinema theatre to other parts of the building or to the outside. One door, which has no handle, is located in the front left corner of the room. This door can only be opened from an adjacent room and can therefore not be used to exit the theatre. The door is not equipped with an emergency exit sign.

In the event of an evacuation visitors can use one of two exits, namely the main exit or the emergency exit, see Fig. 4. Both doors of the exits are black steel doors that are clearly distinguishable from the red walls of the cinema theatre. There are also standard emergency exit signs above both the main and emergency exit. The main exit leads to the ticket hall via a corridor and is also the ordinary entrance and the normal exit for non-emergency situations. This means that it is the most frequently used and therefore the one that visitors are most familiar with. The emergency exit, which is never used for non-emergency situations, leads directly to the outside. The door is equipped with a panic bar and a sign with the text *Not an exit*.

Apparatus and materials

All evacuations were filmed with a video camera that was located in the front left corner of the cinema theatre. The camera was concealed in a black box that was placed next to the screen at a height of two meters. The location provided a good overview of the room. All seats and the main exit were covered by the camera, but the emergency exit was not. However, from the video films it was clear which exit that was used by participants.

The fire alarm was played using the sound system in the cinema theatre and consisted of a pre-recorded message that was preceded by a pulsating tone signal. The message, which was read by a woman, consisted of a call for attention, information that a fire incident had occurred and instructions to

leave through the closest exit and gather outside the building. In the experiments the alarm was activated manually from the projection room when the film had been stopped. The tone signal and the pre-recorded message were repeated until the experiment was terminated.

Green flashing lights were used at the emergency exit in two of the four experiments. The lights consisted of two green light bulbs that were placed above the emergency exit sign, see Fig. 4. During evacuation the lights flashed with a frequency of approximately one Hz (one flash per second). The lights were turned on manually with a remote control when the alarm was activated. In the experiments without flashing lights only the light bulbs were removed, but the emergency exit sign above the door remained.

All participants filled out a questionnaire after evacuation. The questionnaire was divided into three parts that were similar to the parts used in the questionnaire for the office building evacuation described earlier. In the first part participants were asked background questions, namely questions relating to gender and age. The second part contained questions about the evacuation, e.g., their initial location, which exit they chose, if they changed their choice of exit and actions they undertook before beginning to move towards an exit. In the third part participants were asked four questions about the exit they used and two about the exit they did not use to leave the cinema theatre. Apart from minor changes, the six questions used in part three were identical to the six questions about exits in the second part of the office building questionnaire. The main difference was that floor was replaced by cinema theatre in question five.

Procedure

The video camera was started just before the visitors were allowed to enter the cinema theatre. While visitors were entering and taking their seats advertisements were shown on the screen. After a while the advertisements came to an end and film trailers were shown instead. Towards the end of the film trailers, usually in the middle of the last trailer, the film was stopped, emergency lights were lit and the alarm was activated. The participants began to evacuate and were stopped either in the corridor outside the main exit or outside the building if they used the emergency exit. The experiment was terminated when all participants had left the cinema theatre.

In the experiments an observer was present inside the cinema theatre, namely in a seat close to the back right corner. The main purpose of the observer was to control the video camera and the flashing lights and to interrupt the experiment if something went wrong. In order to influence the reaction of others as little as possible the observer was instructed to respond when

everyone else had risen from their seats and to be among the last to leave the room.

When everyone had left the alarm was turned off and the participants were led into the cinema theatre again where they were informed about the evacuation. They were also given the questionnaire, which they filled out while sitting in their seats. The questionnaire was collected immediately and the participants then wrote their home address on a list that was passed around. The list with addresses was only used to send a cinema check and written information about the study to participants.

A total of four evacuation experiments were performed, namely two with and two without green flashing lights at the emergency exit. Information about the experiments can be found in Table 2. The number of participants in the experiments varied between 10 and 17, i.e., only about 20 to 30 percent of the seats were taken.

Table 2. The four evacuation experiments in the cinema theatre.

Experiment	Flashing lights	Show	Number of participants
A	Yes	Late	11[a]
B	Yes	Late	11
C	No	Early	17
D	No	Late	10

[a] Excluding one person who left before the alarm was activated.

Data analysis

The video films were analyzed to determine which exit was used to leave the cinema theatre in the four experiments. However, no significance test was used to investigate if the use of exits differed between the experiments with and without green flashing lights. The video films were also analyzed to obtain information about actions undertaken by participants before they started to move towards an exit. Further information about participants' actions was obtained from the questionnaires.

The questionnaires were used to get background information about the participants, i.e., their age and gender. An in-depth analysis of answers to the questions about characteristics of exits was also performed. Participants could reply either No or Yes to these questions. If they answered Yes they were asked to explain what they meant. These explanations were divided into categories according to Table 1. However, the categories Big, Small and Crowded were not used since they were not relevant for the cinema theatre evacuations.

RESULTS

Evacuation of an office building

The video films show that most participants left their offices promptly, but some sought additional information before they began to move towards an exit. Examples of behaviour that indicated seeking of information was looking out through windows, looking out into the corridor and talking to colleagues. The questionnaires also substantiate that many wanted confirmation of what was happening. One quarter of the participants mentioned that they had performed actions that were aimed at getting more information. The most common action was to look for information at AstraZeneca's intranet, but some also said that they talked to colleagues or looked out through windows.

Other actions that were mentioned in the questionnaire were mainly preparative, i.e., getting ready to leave the building. Examples included logging out or turning off computers, ending phone calls, putting on additional clothes and gathering belongings. One tenth also mentioned that they tried to warn others, encourage others to escape or looked for colleagues, e.g., checked to see that the restrooms were empty.

The analysis of exit choice based on the video films revealed that a slightly larger proportion of participants used the spiral staircases when green flashing lights were used, see Table 3. The proportion of participants who used the spiral staircase was 18% for floors three and seven and 11% for floors four and six. However, this difference was not significant (Fishers exact test, p=.685). The majority of participants, namely 82%, also stated in the questionnaire that they used the central staircase. These results confirm observations from the evacuation, namely that the central staircase was crowded and that few used the east and west staircases. Only 49 participants were in the marked sections of corridor in Fig. 3 during evacuation and only those 49 people were hence included in the analysis of exit choice, see Table 3.

Table 3. Use of exits in the office building evacuation.

Floor	Flashing lights	Exit use	
		Spiral staircase	Other exits
3 and 7	Yes	4	18
4 and 6	No	3	24

Participants' answers to the questions about exits were more extensive than requested. Answers not only related to the mere appearance of the exits, but also to surrounding factors such as action of others. The answers to the six questions about exits are given in Table 4 and include both participants who

used the spiral staircases and those who used other exits. Answers that were given by more than four people, i.e., more than 5% are underlined and bold in the table.

Table 4 shows that size or capacity of the exit was an important feature. Twelve participants, who all used the central staircase, wrote that the large size or large capacity were encouraging features. Also, four participants, who all used the central staircase, wrote that the small size or the limited capacity were discouraging features for other exits. Ironically, since many used the central staircase it became crowded, whereas other staircases were almost empty. The large number of people in the central staircase was also mentioned as a discouraging factor.

Table 4. Answers to the six questions about exits arranged by category.

	Used exit				Other exit	
Category	1. Stand out	2. Different	3. Encourage	4. Discourage	5. Special	6. Discourage
Clearly marked	2	2	3	0	0	0
Flashing light	2	0	0	0	3	0
Known exit	1	0	4	0	0	0
Others used it	2	1	3	0	0	0
Closest	11	3	5	0	0	0
Big	2	4	12	0	0	0
Small	0	0	1	0	0	4
Crowded	5	3	0	6	0	0
Other	2	3	7	2	3	5

Relatively few mentioned the green flashing lights. Only two of the four participants who used the spiral staircases on floors with flashing light pointed out the lights. Three participants who used the central staircase also pointed out the lights. Another factor that was mentioned was the distance to the chosen exit, i.e., a short distance was perceived as an encouraging factor.

Evacuation of a cinema theatre

The films from the evacuations revealed that participants responded promptly. Most people started to prepare to escape when the message had been played once. Typical behaviour before beginning to move towards an exit included putting on additional clothes and gathering belongings. These actions were also frequently mentioned in the questionnaires.

The importance of the green flashing lights on exit choice was apparent in the cinema theatre experiments, see Table 5. Everyone used the emergency exit in the experiments with flashing lights, whereas the emergency exit was not used at all in the experiments without flashing lights. In experiments A and D two participants initially headed towards one exit, but later turned around and used the other exit to leave the cinema theatre.

Table 5. Use of exits in the cinema theatre evacuations.

Experiment	Flashing lights	Exit use	
		Emergency exit	Main exit
A and B	Yes	22	0
C and D	No	0	27

Participants' answers to the questions about exits were more extensive than requested. Answers related to both the appearance of the exits as well as surrounding factors, e.g., actions of others. Table 6 shows that participants' answers to the six questions about exits for the experiments with and without green flashing lights. Answers that were given by more than three persons are underlined and bold in the table. Table 6 shows that the green flashing lights were seen as an encouraging feature that made the emergency exit stand out. It is also worth mentioning that four participants in the experiments without flashing lights wrote that a special feature of the emergency exit was that it was equipped with an emergency exit sign. However, these individuals did not mention the emergency exit sign at the main exit even though they used that exit to leave the cinema theatre and not the emergency exit.

Table 6. Answers to the six questions about exits arranged by category for experiment with and without flashing lights.

Category	With flashing lights						Without flashing lights					
	Used exit				Other exits		Used exit				Other exits	
	1. Stand out	2. Different	3. Encourage	4. Discourage	5. Special	6. Discourage	1. Stand out	2. Different	3. Encourage	4. Discourage	5. Special	6. Discourage
Clearly marked	3	1	2	0	0	0	3	0	0	0	4	0
Flashing light	**20**	**14**	**15**	0	0	0	0	0	0	0	0	0
Known exit	0	0	0	0	0	0	2	3	0	0	0	0
Others used it	0	0	1	0	0	0	3	0	1	0	0	0
Closest	0	0	0	0	0	0	2	3	0	0	0	0
Other	1	3	4	1	3	3	2	0	1	1	1	3

DISCUSSION

In the present study evacuations were performed in two settings, namely an office building and a cinema theatre. These two settings differ in many ways, but one of the most important differences is the familiarity with the building. The occupants of an office building typically know the building quite well since they spend considerable time there. Cinema visitors on the other hand are less familiar with the cinema theatre since they spend quite limited time there.

In the office building emergency exits were chosen slightly more frequently if green flashing lights were used, but the difference was not significant. Also, the lights were mentioned by only a few participants, which suggest that they were either not perceived as important features of the exits or were not noticed at all. It is believed that the latter explanation is the most likely, i.e., that the flashing lights were not noticed, as the green strobe lights (xenon tube) that were used in the brightly lit corridors probably did not provide enough contrast and thus not sufficient sensory affordance to be noticed by participants. It is therefore recommended that similar experiments are performed with more powerful lights.

Because the lights did not provide sufficient sensory affordance other factors most likely became more important. The fact that the participants were familiar with the office building probably influenced what features of the exits were identified. Many mentioned the size or capacity of the stairs as important factors. The large capacity of the central staircase was encouraging and the limited capacity of other staircases was discouraging. These factors are actually not part of an exit's exterior appearance, but instead require knowledge about what lies behind the door, i.e., familiarity with the building. Ironically, the large size probably influenced many participants to use the central staircase, which lead to crowding and unnecessarily long evacuation times. It would have been better if people used other exits to a greater extent, which may be possible to achieve with more appropriate lights at the exits.

The potential effectiveness of green flashing lights for influencing exits choice was clearly demonstrated by the cinema theatre evacuations. Almost all participants mentioned the flashing lights as a feature of the exit that made it stand out, which suggests that the system provided sufficient sensory affordance. Many also mentioned that the flashing lights also encouraged people to use the exit, which can be a result of cognitive affordances introduced by the system. The system possibly signals a change from passive to active, since the lights begin to flash when the alarm is activated. This transition may help potential users to understand that the exit is now available for use and that it is allowed to use it.

The experiments pose an interesting question: How important is the colour of the flashing lights? In the experiments only green lights were tested, but previous studies suggests that the colour can be of great importance [7,9]. Some colours are known to have established meanings within populations [14]. Red is often associated with stop or danger, whereas green is often associated with *go* or *safety*. These established meanings of colours can potentially cause conflicting cognitive affordances. Although red flashing lights at an exit can provide powerful sensory affordance, the colour may tell potential users that they should keep away. This information is in conflict with the sign that instructs people to use the exit in the event of an emergency. However, use of colours must be seen in the context of culture, since the established meanings may differ between populations.

In this study focus has been on the appearance of exits and more specifically on how green flashing lights influence people's perception of exits. However, results indicate that there are many other factors not related to exit design that influence exit choice during evacuation. One example of an important factor is the actions of others, i.e., social influence. If someone begins to use an exit it is probable that others will follow and that flashing lights or other types of systems may not be sufficient to convince people to change their choice of exit. However, the appearance of exits is undoubtedly important when people decide what exits to use in the event of a fire emergency. Attention must therefore be focused on exit design when buildings are planned and built.

One limitation of the study is the small number of participants that took part in the cinema theatre evacuations. On average only a quarter of the seats were taken, which presumably influenced participants' exit choice. People would possibly have used both exits even if one was equipped with flashing lights if the cinema theatre was full. It is therefore suggested that more experiments with flashing lights at exits should be performed to investigate how the system influences exit choice for cinema theatres that are filled to capacity.

CONCLUSIONS

The present study suggests that green flashing lights at exits can be used to influence exit choice, but that the effectiveness of the system depends on the setting. Flashing lights, if used appropriately, make the exit stand out and encourages people to use it. One possible explanation is that the lights begin to flash when the alarm is activated, which signals a transition from passive to active. This transition can help potential users to understand that the exit is available for use.

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