INVESTIGATION INTO THE INTERACTION OF PEOPLE WITH SIGNAGE SYSTEMS AND ITS IMPLEMENTATION WITHIN EVACUATION MODELS

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DECLARATION

I certify that this work has not been accepted in substance for any degree, and is not concurrently being submitted for any degree other than that of Doctor of Philosophy (PhD) being studied at the University of Greenwich. I also declare that this work is the result of my own investigations except where otherwise identified by references and that I have not plagiarised the work of others.

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ABSTRACT

Signage systems are widely used in buildings in accordance with safety legislation and building standards. These aim to provide general information and safety messages to occupants, and assist them in wayfinding during both circulation and evacuation. Despite the fact that signage systems are an important component in building wayfinding systems, there is a lack of relevant data concerning how occupants perceive, interpret and use the information conveyed by emergency signage. The effectiveness of signage systems is therefore difficult to assess and is not correctly represented in any existing evacuation models.

In this dissertation, this issue is addressed through two experiments and the modelling of the interaction with emergency signage based on the empirical findings. The first experiment involved measuring the maximum viewing distance of standard signs at various angles to produce an empirical representation of signage catchment area. The second experiment involved measuring the impact of a signage system on a population of 68 test subjects who were instructed to individually vacate a building by their own efforts. The evacuation path involved a number of decision points at which emergency signage was available to identify the appropriate path. Through analysis of data derived from questionnaires and video footage, the number of people who perceived and utilised the signage information to assist their egress is determined.

The experimental results are utilised to enhance the capability of the buildingEXODUS software. Firstly, the signage catchment area is revised to more accurately represent the visibility limits of signage than previously modelled according to the definition of signage visibility by regulations. Secondly, the impact of smoke on signage visibility is introduced and the representation of the impact of smoke on occupant evacuation performance is improved based on existing published data. Finally, the signage detection and compliance probabilities are assigned values based on the experimental data rather than the ideal values previously assumed. The impact that the enhanced signage model has on evacuation analysis is demonstrated in hypothetical evacuation scenarios. The new signage model is shown to produce a more representative and realistic estimate of expected egress times than previously.

It is hoped that this dissertation will improve our understanding of a key phenomena – the interaction of people with signage, and allow interested parties (e.g. engineers, safety managers and designers, etc.) to more effectively and credibly examine the impact of signage systems upon pedestrian and evacuee movement.

CONTENTS

Xie, H., Filippidis, L., Galea, E.R., Blackshields, D., Lawrence, P.J., (in press) Experimental analysis of the effectiveness of emergency signage and its implementation in evacuation simulation, *Fire and Materials*.

Xie, H., Filippidis, L., Galea E.R., Gwynne, S., Blackshields, D., and Lawrence, P.J., 2009. Experimental study of the effectiveness of signage upon an evacuating population. *Proceedings of the 4th International Symposia on Human Behaviour in Fire*, Robinson College, Cambridge, UK, Interscience Communications Ltd: London, pp.289-300, ISBN 978-0-9556548-3-1.

Xie, H., Filippidis, L., Gwynne, S., Galea E.R., Blackshields, D., Lawrence, P.J., 2007. Signage legibility distances as a function of observation angle, *Journal of Fire Protection Engineering*, 17(1), pp.41-64.

Xie, H., Filippidis, L., Galea E.R., Gwynne, S., Blackshields, D., Lawrence, P.J., 2005. Experimental study and theoretical analysis of signage legibility distances as a function of observation angle. In *Pedestrian and Evacuation Dynamics 2005*, N. Waldau,P. Gattermann (eds.), Springer: Berlin, pp.131-143, ISBN 978-3-540-47062-5.

TABLES and FIGURES

Chapter 1

Introduction

This chapter begins with a description of the background and motivations of the research together with the questions raised, followed by the objectives that need addressing and the corresponding approach. Finally, the structure of the dissertation is described at the end.

1.1 Research Background, Motivations and Questions

Common activities such as commuting, working, shopping and socialising etc., consist of occupants (often in large numbers) gathering together and circulating in building enclosures. In order to accommodate occupants performing these activities and fulfil the expectations of users, buildings are becoming larger and more complex in structure through the increasingly ambitious designs of architects. These complex designs pose a problem for building occupants when they need to find a path to desired destinations or a final exit [Passini, 1992]. The situation could be worse in an emergency that requires an evacuation: e.g. fire, terror attack, gas or chemical leak etc. Such an emergency is often accompanied by a spread of harmful hazards inside the enclosure and may result in loss of some routes and function of the building (e.g. the Düsseldorf airport fire in 1996 [Weinspach *et al.*, 1997], the Gothenburg dance hall fire in 1998 [Comeau & Duval, 2000], the Cook County Administration Building fire in 2003 and the Station Nightclub Fire in 2003 [Grosshandler *et al.*, 2005a]). The occupants have to respond to the abnormal stimuli, avoid the hazardous conditions and find an escape route, which may not be the same one as they normally use, leading them to a place of relative safety or the exterior of the enclosure under conditions of stress. In brief, the increasing complex and size of today's building designs make an efficient wayfinding under both general circulation and emergency conditions a crucial problem to be solved to enhance building occupant's experience and safety [Arthur & Passini, 1992; Filippidis *et al.*, 2003, 2006, 2008; Xie *et al.*, 2007, 2009; Veeraswamy *et al.*, 2009; Akizuki *et al.*, 2009, 2010].

1.1.1 The Role of Signage System in Wayfinding

Wayfinding, within the building evacuation context, is a dynamic process by which an individual located within an unfamiliar and/or arbitrarily complex enclosure attempts to find a path that takes them to a place of safety or to an exit open to the exterior of the enclosure, by continuously reading, interpreting and representing the space they travel through. One widely used method to tackle the wayfinding difficulty in workplaces and public buildings is to provide supporting information through signage systems* [Arthur & Passini, 1992]. The provision of signage attempts to address the wayfinding issue from two perspectives. Firstly, in large and complex buildings, the enclosure may not have an intuitive layout, while the information available may be insufficient for occupants to make a quick and appropriate decision when an evacuation is required. For instance, it may not be possible to have a direct visual access to the desired target or exits in some places, while in some other places there may be multiple choices of routes and doors without clear clues about which one is appropriate or better. In both cases, additional information is required to assist occupants in making a choice. Secondly, occupants tend to leave the enclosure by the same route they enter or the routes with which they are familiar [Sime, 1985; Benthorn & Frantzich, 1999; Shields & Boyce, 2000]. This behaviour may reduce the efficiency of an evacuation, as alternative and unfamiliar escape routes/exits may not be utilised to their full potential, while main and familiar escape routes/exits may be overcrowded. In these situations, the provision of signage can supply supporting information to occupants (especially those who are unfamiliar with the layout of the enclosure) and encourage them to utilise all available means of escape.

The need for workplaces and public buildings to have proper signage systems installed has been recognised and prescribed by various British health and safety legislation, such as the Fire Protection Act 1971, the Health and Safety (Safety Signs and Signals) Regulations 1996, the Fire Precautions (Workplace) Regulations 1997 and the Regulatory Reform (Fire Safety) Order 2005. Fire Protection Act 1971 for instance, requires that exit and directional signs must be installed at

> "*Where an exit cannot be seen or where a person escaping might be in doubt as to the location of an exit…*"

* Signage can provide guidance, warning and mandatory message to building occupants. According to the message represented, safety signs can be categorized into five types: prohibition signs, hazard signs, mandatory signs, fire equipment signs and safety condition signs [BS5499-1:2002]. The safety condition signs are of special interests to this research as they convey the safety message indicating the location of exit and the direction of escape route. In the following context safe condition signs, including escape route signs, exit signs and fire exit signs with directional designation, are the only type of signs that will be addressed in this dissertation, unless otherwise stated.

The provision of exit and directional signs is intended to indicate the location of exit doors and direction of escape routes. It is expected that the information conveyed by these signs will facilitate occupants' selection of exit route/exit door during an emergency, thus expedite the evacuation.

Safety legislation and building standards attempt to enforce the effectiveness of signage systems by prescribing the design, installation and maintenance criteria of signage systems [the Health and Safety (Safety Signs and Signals) Regulations 1996; BS5499-1:2002; BS5499-4:2000; ISO 3684-1:2002; ISO 7010:2003; ISO 16069:2004]. The implied assumption is that if the signage system is compliant it will be effective in conveying the specified information to the occupants and that this will be correctly interpreted and utilised by the occupants. However, the interaction between the occupants and signage, in reality, is a complex process which is influenced by a series of physical, environmental, cognitive and psychological factors [Filippidis *et al.*, 2003, 2006].

First of all, the sign must be physically visible [Filippidis *et al.*, 2001; Xie *et al.*, 2005, 2007], while the visibility of signage is influenced by the nature of the sign (e.g. size, type, etc) [BS5499-4:2000], the level of ambient lighting [BS5499-4:2000, Wright *et al.*, 2001a], the presence of smoke [Jin 1978, 1997, 2008; Jin & Yamada 1985; Rea *et al.*, 1985; Collins *et al.*, 1992; Wong & Lo, 2007; Zhang & Rubini, 2009, 2010] and the presence of visual clutter within the environment [Sixsmith *et al.*, 1988; Ozel, 2001; Akizuki *et al.*, 2009, 2010].

Even if the sign is physically visible, the likelihood of the occupants perceiving the sign is influenced by their attentiveness [Arthur & Passini, 1992]. Further, assuming that the sign is physically visible and that the occupants perceive the sign, an occupant following the information conveyed by the sign is subject to cognitive factors such as their interpretation of the information and psychological factors such as their desire to comply with the instruction. As a result, the actual effectiveness of wayfinding signage systems may not be assumed.

Several previous disasters (such as the Beverly Hills Supper Club fire in 1977 [Best, 1977]; the Scandinavian Star Disaster in 1990; the Cook County Administration Building fire in 2003; the Station Nightclub Fire in 2003 [Grosshandler *et al.*, 2005a, 2005b]) have demonstrated that signage systems may not function according to design. A poor signage system design may occasionally be to blame, but the fact that people may not make use of the signs has frequently been overlooked. Most of these factors mentioned are well beyond the scope of building guidelines and standards, as they do not quantify the effectiveness of signage systems, or leave it to performance-based approach to evaluate as part of safety design (see Section 1.1.2). This thesis presents research that aids in this quantification.

1.1.2 Building Occupant Safety and Evacuation Modelling

Building safety has been regulated by building standards since the 1900s [Bryan, 2002]. Originally, safety was regulated through a prescriptive approach, which involves specific restrictions into regulations and standards (e.g. Fire Precaution Act 1971) to which building design must conform. For instance, the number of exits in a building must be more than the prescribed minimum number; the maximum travel distance inside the building must not be longer than the prescribed maximum allowed distance, and the occupant capacity must not exceed the maximum number of persons which can be safely accommodated in the building. The prescriptive approach provided a practical means for building design and management. If the designer followed these guidelines the building was deemed to be safe, although safety levels were not demonstrated. This approach has its limitations [Oleszkiewicz, 1994]: (1) it does not allow an immediate inclusion of new technologies, products, methods; (2) it can not cope with the demand for larger and more complex modern building designs; (3) it does not fully address the influence of occupant behaviour during an evacuation [Gwynne *et al.*, 1999a; Gwynne, 2000]; and (4) indeed, many simplifying assumptions are embedded within the regulatory frameworks.

To address some of these issues, a performance-based approach has been adopted [Bukowski & Tanaka, 1991; Oleszkiewicz, 1994; Watts, 1994] over the past few decades. This new approach, within the context of building occupant safety, establishes the safety objectives to be achieved by the design as a whole [Watts, 1996; Bukowski, 1996]. Design professionals have more flexibility over the materials, products and methods to achieve these objectives. However, this approach requires an additional step: to assess whether the safety objectives of a building design are met by demonstrating the performance levels met. For instance, given the likelihood of a fire scenario, an acceptable performance-based design needs to show that the available safe-escape time (ASET) is significantly greater than the required safe-escape time (RSET) [ISO/TR 13387-8:1999; ISO/TR 16738:2009]. Here the ASET is a measurement of time between the start of the fire and the onset of the conditions that make the enclosure untenable for occupants, while the RSET is the amount of time between the start of the fire and the moment when the last occupant reaches a place of safety.

Performance-based design requires the ability to calculate the RSET value. The rapid development of computer modelling technology in the latter part of the last century provided a convenient method to conduct the assessment required by the performance-based approach. As early as in the 1970s, researchers started using computer simulation to study pedestrian movement and evacuation related issues [Francis & Saunders, 1979; Stahl, 1982].

There are several benefits of using computer simulation. Firstly, computer simulation is flexible and capable of testing various designs and procedures; it is only restricted by the capabilities of the model development and available hardware resources. Secondly, there are almost no restrictions and ethical issues in simulating emergency scenarios, even those incidents including harmful hazards [Galea *et al.*, 1996a, 1996b; Gwynne *et al*., 2001; Jiang, H., *et al*., Galea *et al*., 2008]. Thirdly, running computer simulation is cost efficient. A repeat of the simulations does not considerably increase the cost except extra computing time. Finally, computer simulation can provide, subject to model implementation, the details of the simulated scenario, including visualisation and a variety of data outputs that can help the user inspect and analyse the process.

The research and development efforts in the field of evacuation modelling have been mainly oriented towards two trends [Sime, 2001]. The first trend attempts to model an evacuating population as an analogy of hydraulic flow, with the simulated occupants having identical traits, following pre-calculated routes, with limited behaviours represented. This often contrasts with reality, which involves complex people-people, people-structure and people-environment interactions [Gwynne *et al.*, 1999a; Gwynne, 2000]. The actual process can be adaptive and sensitive to the changing conditions as well as available information, while the evacuation performance is influenced by occupant behavioural responses accordingly [Gwynne *et al.*, 1999a; Gwynne 2000; Sime, 1984, 2001; Bryan 2002; Proulx & Fahy, 2008]. Until recently, the majority of computational evacuation models have followed this first trend.

To address this issue, recently more efforts have been directed towards the second and more sophisticated trend: an attempt to represent realistic behaviour within the models to examine the influence of behavioural factors during an evacuation. There are many types of occupant behaviour, which can be broadly categorized as local behaviour and global behaviour. The local behaviour dictates an occupant's response to the prevailing conditions in close vicinity to them. It deals with occupant-occupant (e.g. herding, competing, overtaking), occupant-structure (e.g. detecting and avoiding obstacles, travelling on elevators and escalators) and occupant-environment (e.g. walking through or redirecting from smoke and other hazards) interactions. The global behaviour dictates an occupant's primary goal and their overall strategy to achieve this goal. It effectively influences the occupant's selection of escape routes and final exit doors.

Whereas occupant small-scale behaviour has been studied through mathematical modelling [Helbing, 1991; Helbing & Molnár, 1995; Still, 2000; Was *et al.*, 2006], analysis of data collected through investigation [Thompson, 1994], observation [Thompson, 1994; Gwynne & Boswell, 2009] and experiments [Hoogendoorn *et al.*, 2003; Daamen *et al.*, 2003; Daamen, 2004; Moussaïd *et al.*, 2009] in the past decades, there has been relatively insufficient research [Benthorn & Frantzich, 1999; Shields & Boyce, 2000] addressing occupants' escape route/exit choice in a larger perspective – a hindrance to modelling that reflects the complexity of occupant wayfinding behaviour and decision-making process. Most pedestrian (including evacuation and circulation) computer models [Kuligowski, 2008] bypass complex route calculation by following an "optimistic" assumption: the choice of escape route/exit is simulated independently of wayfinding information in the environment. To compensate for this, agents are simulated as understanding the routes available, excluding a key factor (wayfinding information) in route/exit selection and preventing the models from examining the impact of the design of different signage systems. A key factor in the representation of wayfinding within these models was the lack of relevant and sufficiently detailed data [Filippidis *et al.,* 2003, 2006].

1.1.3 Research Questions

In order to understand how effective the signage system is in practice and correctly represent it within evacuation modelling, several questions need to be answered.

Question 1: How do people interact with signage in buildings?

This question can be broken down into several more specific questions addressing the interaction with signage from three aspects.

(Q1.1) *Visibility of sign*: What is the definition of signage visibility? What are the corresponding requirements to achieve the visibility in current legislation and standards? What is the physical extent within which people can reliably resolve the sign? What are the conditions for reliably resolve the sign?

(Q1.2) *Perception*: What is the current understanding on how people interact with signage? Given that the sign is visible, are people always able to perceive the sign? If not, how likely is it that people perceive or register seeing the sign? What are the factors that may influence the perception of the sign?

(Q1.3) *Interpretation and compliance*: Given that people already perceive and read the sign, what is the likelihood of people correctly interpreting and complying with the information conveyed by the sign?

It is possible that occupants may encounter smoke during an emergency evacuation. Indeed, it is under these conditions that the influence of signage may be most important.

Question 2: How does the presence of smoke influence people's interaction with signage and their evacuation behaviour?

(Q2.1) How does smoke influence the visibility of signs?

(Q2.2) How does smoke influence people's travel speed and evacuation behaviour?

(Q2.3) What are the results and findings from relevant studies?

Finally, questions are raised regarding the representation of the interaction with signage and the influence of smoke in computer models.

Question 3: How are evacuation models influenced by the understanding of the interaction with signage and the impact of smoke?

(Q3.1) How are signage systems currently modelled in existing models?

(Q3.2) How is the impact of smoke upon the interaction with signage modelled in existing models? How is the impact of smoke upon people's travel speed and evacuation behaviour modelled in existing models?

(Q3.3) What are the limitations of the current representation of the interaction between occupants and signs? What are the limitations of the current representation of the influence of smoke? How can the models be improved?

1.2 Research Objectives and Approach

Given the important role of signage in guiding building occupants in an evacuation, and the need to understand the extent of the impact of signage on occupants' evacuation behaviour, this research is proposed to

- review relevant research on signage and the representation of the interaction between occupants and exit signs in existing models;
- investigate the interaction between occupants and exit signs through an experimental approach;
- review the experiments conducted to study the impact of smoke on occupants and analyse the experimental results;
- utilise all of the results obtained to develop a comprehensive signage model which improves the representation of the interaction between occupants and signs including the influence of smoke in evacuation modelling.

This research takes the following steps to answer the questions posed in Section 1.1.3.

How do people interact with signage in buildings? How does the understanding of this interaction influence the modelling?

In order to answer these questions,

- a review of the current understanding of human interaction with signage is presented;
- a review of the evacuation models currently available is presented;
- a series of experiments specifically designed to examine people-signage interaction are discussed;
- the experimental results are analysed;
- the findings obtained from the analysis are incorporated into the development of a new signage model;
- the impact of the signage model is demonstrated through test case studies, while the improvement achieved is shown by comparing the simulation results with those generated by previous modelling approach.

Firstly, the current research knowledge about how people interact with signage is reviewed, including the results and findings obtained from previous experimental and theoretical studies. Since the design, selection and position of signs must comply with relevant safety legislation and building standards, the measures addressing the visibility and effective use of signs in these regulations are reviewed to find out whether they fulfil the purpose of the regulations. Several selected evacuation models are also reviewed to gain insight into how signage systems are currently modelled, including how simulated agents perceive signage during an emergency evacuation and how the information conveyed by signage influences their evacuation behaviour. The purpose of these reviews is to identify what knowledge is currently lacking in the understanding, what are the limitations of the current evacuation models with respect to representing signage, and how they can be improved.

Secondly, to address the lack of information on the interaction between occupants and signs identified from the review and analysis, a series of experiments are designed and conducted to study the interaction and collect the crucial data. The experimental study is divided into two phases.

Phase 1 of the trials aims to assess the physical extent within which people are able to resolve a sign and perceive information conveyed by the sign. This is achieved by measuring the maximum viewing distances of standard exit/fire exit signs in several viewing angles and outlining their effective catchment areas. The results are then compared against the visual catchment areas estimated according to the guidance set out by relevant standards.

Phase 2 of the trials focuses on the process of occupant interaction with the signs in a real built environment. During the trials, individual participants will be put through a test area within a selected university building under (presumed) conditions of stress. Their interaction with those preinstalled signs along the exit routes will be examined, including

- whether the participants perceive any exit sign(s) or they miss them,
- if they do, when and where they become aware of the sign(s),
- and how the information conveyed by the sign(s) influences their selection of exit route/exit door.

Finally, the data collected from the experimental trials will form the basis for modelling the interaction in the new signage model. This model takes into account the visibility of signs (results from Phase 1 of the trials) and the influencing factors examined in the experimental study of the interaction (results from Phase 2 of the trials).

How does the presence of smoke influence people's interaction with signage and their behaviour?

Given that fire smoke may be present during an evacuation, occupants may have to travel and/or find their way through smoke. The presence of smoke inevitably influences their physiological well-being, their abilities to discern the environment and travel at desired speeds, and consequently, influences their evacuation behaviour [Purser, 1996, 2001, 2003, 2008; Proulx & Fahy, 2008]. The obscuration effect of smoke also reduces an occupant's ability to discern a sign. Therefore, it is important to take the presence of smoke into account when representing the interaction with signage. This is achieved by implementing an adapted Jin's model [1978, 1997, 2008] to estimate the impact of smoke on signage catchment area. The impact of smoke on occupants' egress performance and behaviour has been studied by several researchers with different objectives [Jin, 1978, 1997; Jin & Yamada, 1985, 1989; Wright *et al.*, 2001a, 2001b; Galea *et al.*, 2001; Frantzich & Nilsson, 2004]. This impact of smoke is currently included in the model developed [Galea *et al.*, 2004]; however, this development relies on third party data available then. An attempt is made to compare the experimental conditions examined by these researchers and integrate the experimental results to form a comprehensive description of the impact of smoke to improve the existing model.

1.3 Structure of Dissertation

In Chapter 2, a review of the current understanding on occupant interaction with signage is presented at the beginning. The guidance on the design and use of signage by relevant legislation and standards is discussed. The experimental studies on the impact of smoke are introduced. Also included is a review of seven selected evacuation models, with the emphasis on how these models represent occupant wayfinding process, occupant interaction with signage and the impact of smoke.

In Chapter 3, the buildingEXODUS evacuation model is described as it is the selected platform for implementing and demonstrating the new signage model. The selection of this model is based on the consideration that buildingEXODUS is a behavioural model which allows new behavioural rules to be added and tested, and that the model is readily available to the author.

Chapter 4 and Chapter 5 attempt to establish the effective visible area of signage. While Chapter 4 describes the theoretical analysis of the visibility of signage and the design of Phase 1 of the trials, Chapter 5 presents the experimental results and a comparison with the definition of visibility of signage by legislation and standards.

In Chapter 6, the design of Phase 2 of the trials is described based on the analysis of the interaction between occupants and signs. Chapter 7 presents the data collected from the trials described in Chapter 6 as well as the results from analysing the data. Based on the experimental results, the development of a new signage model is described in Chapter 8.

Chapter 9 presents two demonstration cases using the new signage model and a comparison with the simulation results generated by the previous modelling approach, i.e. the earlier version of the buildingEXODUS model.

Chapter 10 and Chapter 11 discuss the impact of smoke upon evacuating occupants. Chapter 10 focuses on the visual obscuration effect of smoke upon the visibility of exit signs, while Chapter 11 addresses the impact of smoke on occupant's movement and behaviour.

Finally, the entire work is summarised in Chapter 12, which also includes the suggestions for further development and future research.

Figure 1.1 shows the relationship of these chapters in an overview of this dissertation.

It is hoped that this dissertation will provide an invaluable contribution to the field – improving our understanding of key phenomena, representing these phenomena in algorithmic form, allowing engineers and researchers to more effectively and credibly examine the impact of signage systems upon pedestrian and evacuee movement.

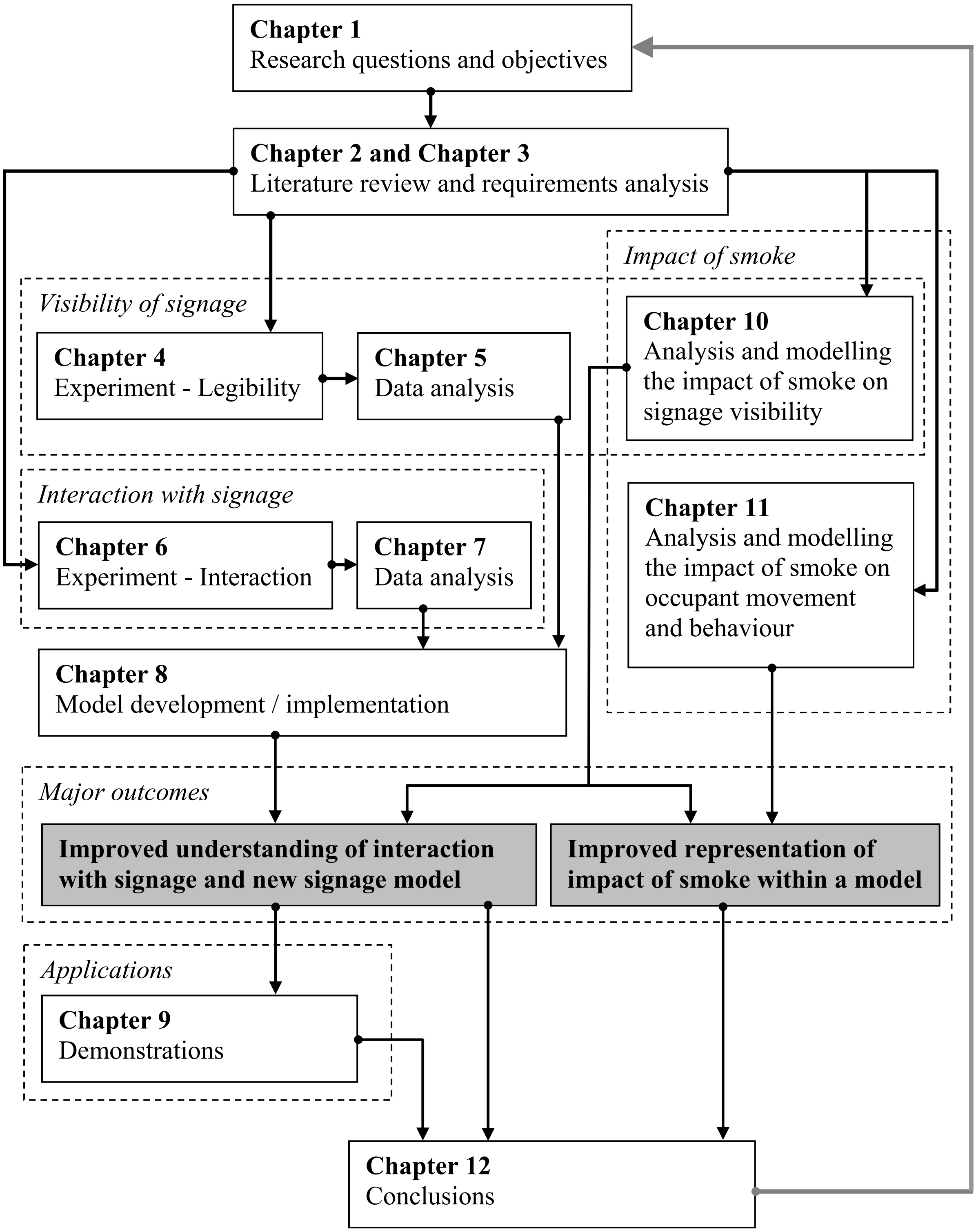


Figure 1.1: An overview of the structure of the dissertation.

Chapter 2
Literature Review

In this chapter, a literature review is conducted to give an overview of the research questions presented in Section 1.1.3 of Chapter 1. This review addresses the interaction between occupants and signs from four perspectives: (1) the current understanding of the interaction, (2) the guidance on design and use of signage provided by legislation and standards, (3) the impact of smoke, and (4) the current approach of representing the interaction in evacuation models.

As this research also focuses on the simulation of the impact of signage on an evacuating population, emphasis is given on evacuation modelling through the introduction of seven evacuation models. The selection of these models is based on the fact that they are representative in the development of modelling approaches; and of them, three explicitly attempted to represent the impact of signage on agents in simulations. These seven models are sorted according to the space representation used, as not only does it influence the modelling approach adopted by the developers, but it also influences the representation of occupant behaviour [Gwynne *et al.*, 1999b; Gwynne, 2000]. These models will be briefly described, with emphasis on how occupant wayfinding process, occupant interaction with signage and the impact of smoke on occupants are implemented (some models may not address all three aspects).

The objective of this review is to gain insight into the current knowledge on the interaction of people with signage, the influencing factors involved, the practice reflected in relevant safety legislation and building standards as well as existing evacuation models, and also to identify what knowledge is still lacking in the understanding and how this proposed research on signage can bring improvement to the representation of the interaction in evacuation models.

2.1 The Understanding of the Interaction between Occupants and Signage Systems

An effective use of signage systems to aid occupant wayfinding depends on two key aspects: (1) the quality of the signage information conveyed and (2) the uptake of the information by occupants.

2.1.1 The Provision of the Signs

The first aspect concerning an effective use of signage systems (i.e. the quality of the information conveyed by signage) primarily relates to the provision of the signs, including design and position of signs. The design of signs [BS5499-1:2002; BS5499-4:2000; ISO 3684-1:2002; ISO 7010:2003] should ensure that the information conveyed in the form of text and graphical symbol achieves a good level of comprehensibility amongst the building users; and the critical details on the signs have a good level of legibility. When considering the legibility of the signs, it should also take account of the abnormal situations such as that there might be fire smoke [Jin, 1978, 1985, 1997, 2008] and mains-failure [BS 5266-7:1999] in the enclosure. The position of signs [BS5499-4:2000; ISO 16069:2004] should ensure the signs are provided at places where direct sight of an exit is not possible and doubt may exist about its location. The directional indication of the signs should be consistent with the intended primary escape route, so that the occupants can always reach a place of safety or a final exit if they follow the signs. When considering the number of signs needed, the design should avoid two cases: too many and too few signs. The former may cause an overload of information, while the latter may pose difficulty for the occupants to follow the signs. In summary, measures should be taken to ensure that the signs are provided as requested and deliver simple, clear, consistent and optimum amount information to the occupants [Arthur & Passini, 1992; BS5499-1:2002; BS5499-4:2000; ISO 16069:2004].

In the UK, the provision of the signs has been extensively addressed by relevant legislation and standards. British legislation [the Health and Safety (Safety Signs and Signals) Regulations 1996; the Fire Precautions (Workplace) Regulations 1997; the Regulatory Reform (Fire Safety) Order 2005] for instance, requires formal risk assessment to be carried out to determine the location where there is a need for signs. British and international standards [BS5499-1; BS5499-4; the 92/58/EEC Directive; ISO 3864; ISO 6309; ISO 7010; ISO 16069] explicitly prescribe the design, selection of the type of sign, mounting positions, lighting and maintenance etc. The evolvement of the provision of the signs and the method for estimating the visibility of signs in relevant legislation and standards are further described in Section 2.2.

2.1.2 The Uptake of Signage Information

The second aspect concerning an effective use of signage systems relates to occupants' uptake of the information conveyed by the signs. Despite the extensive guidance on the provision of the signs, there is little information in safety legislation and standards concerning how effective signage systems are in practice. Therefore, it is often assumed by designers, engineers and building officials that if the signs, which meet the design and installation criteria, are present in a building, occupants will be able to perceive and interpret the signs, and comply with the information conveyed [Benthorn & Frantzich, 1999]. However, previous disasters (such as the Beverly Hills Supper Club fire in 1977 [Best, 1977], the Scandinavian Star Disaster in 1990, the Cook County Administration Building fire in 2003, the Station Nightclub Fire in 2003 [Grosshandler *et al*., 2005a, 2005b]) have demonstrated that signage systems were under-used. This problem of under-using emergency exit signs in evacuations raised the concerns about the ambiguity in the effectiveness of signage systems and the requirement to improve the design of signage systems as an aid for wayfinding. To achieve this goal, a good understanding of the interaction between occupants and signs is needed.

The interaction between occupants and signs can be divided into three phases: perceiving the sign, interpreting the information conveyed by the sign and subsequent decision-making process [Filippidis *et al.,* 2003, 2006]. First of all, the sign must be visually perceivable to occupants. For a sign to be perceivable, two conditions must be met: the occupant must be located within a certain distance range to the sign in order to resolve it, and the sign must fall in the occupant's field of vision [Werner, 1991; Henson, 1993] to be seen. If the conditions allow the sign to be seen, how the occupant will perceive the sign, interpret and act on the signage information is influenced by their attentiveness [Arthur & Passini, 1992], their interpretation of the information, their desire to believe and follow the information and the influence of other occupants and conditions. Therefore, three aspects of occupant interaction with signage need to be addressed successively: (1) the visibility of sign, (2) the perception of sign (i.e. phase 1 of the interaction - the process of attaining awareness of a sign through visual sense) and (3) the interpretation of signage information and whether to comply with the information in a decision-making process (i.e. both phase 2 and 3 of the interaction).

2.1.2.1 Visibility of Sign

The visibility of a sign in normal conditions is mainly dealt by the guidance on design of signage systems and is further discussed in Section 2.2.3.1.

Given that fire smoke may be present during an evacuation, it is also important to understand the impact of smoke upon an evacuee's interaction with signage. The impact of smoke upon signage visibility has been extensively studied by Jin [1978, 1985, 1997], Rea *et al.* [1985]; Collins *et al.* [1992], Weight *et al.* [2001a], Wong and Lo [2007], Zhang and Rubini [2009, 2010] through experiments designed and conducted to examine the obscuration threshold (detectability) and legible threshold (readability) of the sign under various test conditions. The results obtained from these experiments show that the participant's ability to discern exit signs deteriorates with the increase of smoke concentrations and irritant level. Apart from these experimental studies, Zhang and Rubini [2009, 2010] analysed the transport of visible light through smoke and proposed a theoretical model to assess the visibility of sign in smoke.

In addition, the impact of smoke upon an evacuee's travel speed was studied by Jin [1978, 1985, 1989, 1997], Weight *et al.* [2001b], Frantzich & Nilsson [2004] and Galea *et al.* [2001]. The results show that the participant's travel speed and pattern of behaviour were also influenced by the presence of smoke. The impact of smoke upon an evacuee's ability to find an exit in an evacuation was studied by Paulsen [1994]. The results show that the traditional exit sign failed to meet the expectation of effectiveness in smoke.

The impact of smoke on signage visibility and occupants' movement and behaviour is further discussed in Section 2.3.

2.1.2.2 Perception

Given a sign is within the visible range, the next question that needs to be answered is whether an occupant will perceive the sign. Perception is the key aspect involved in the interaction, as it directly influences the effectiveness of a signage system.

Signage has been identified as one form of environmental information (along with architectural differentiation, perceptual access and plan configuration) [Weisman, 1981, 1985] that plays an important role in wayfinding. Research on people's wayfinding behaviour *under normal circulation conditions* shows that signage influences people's wayfinding performance [Weisman, 1981; O'Neill, 1991]. For instance, a positive and direct relationship between the number of signs positioned and occupant wayfinding performance (estimated by traverse time, hesitations, and enquiries) was observed in an experimental research study conducted in a health care environment [Carpman *et al.*, 1984]. Another two studies [Corlett *et al.*, 1972; O'Neill, 1991] also demonstrated that redesigned signage systems in university buildings resulted in improved wayfinding performance (a decrease in traverse time, wrong turns, backtracking) at various levels. However, it was also found that the efficacy and importance of signage in aiding people's wayfinding can be limited [Beaumont, 1984]. For instance, Weisman [1985] reported only 18% of mentioned use of wayfinding signs amongst nursing home residents in a study.

So how efficiently do occupants perceive and use exit signs *in an emergency situation*? What are the factors that may influence the signage perception probability?

Sixsmith *et al.* [1988] suggested that people in movement may miss an indication or a target because they may not face the direction in which the clues are located. Similarly, Filippidis *et al*. [2003, 2006] argued that the relative orientation between an evacuee and a sign may influence the likelihood of the evacuee detecting the sign. He proposed that the influence can be described as a detection probability as a function of the relative orientation angle: a sign in the direction of travel is mostly easy to be seen (a 100% probability), while it is almost impossible to detect a sign in the opposite direction of travel (a zero probability); any other relative orientation angle will have a moderate detection probability between 100% and zero. McClintock *et al.* [2001] found through interviewing randomly picked 500 members of the public at a large retail store in the UK that people tend not to notice or recall the location of emergency exit signs under everyday conditions. She explained the findings through the phenomenon 'movement towards the familiar' and the psychological concept 'learned irrelevance'. In a more realistic experiment conducted to simulate an emergency evacuation from a reconstructed section of the ferry 'Scandinavian Star' filled with smoke, Paulsen [1994] reported 4 out of 12 participants failed the task of evacuation with the aid of standard exit signs.

In addition to modelling and experimental studies, researchers tried to interpret people's wayfinding behaviour in a theoretical framework – perceptual psychology. The essence of visual perception and cognition has been studied by Gibson [Gibson, 1977, 1979]. He proposed an important concept of 'affordance' to describe what is afforded by the physical environment for active individuals to perform possible activities; thus affordance links people's perception with their behaviour. This concept was adopted to analyse and explain the recognition of sign, route, exit route/door and subsequent evacuation [Sixsmith *et al.*, 1988; Nilsson, 2009] and circulation [Raubal, 2001] behaviour.

Considering a built environment with occupants attempting to evacuate, the affordances are the preconditions that allow evacuation activities. For instance, a viable exit door in an enclosure provides an affordance for an evacuee to escape through. The presence of an affordance does not mean that the activity will definitely takes place; rather it relates to the likelihood of that activity. Whether the activity occurs depends on the process of visual perceiving and cognizing the affordance in the environment. In the above example of an enclosure with exit door, the evacuee must perceive the door and recognize it as part of a safe exit route before they can consider the door to be an exit option and eventually decide to use it. During this process, supplying additional signage information to indicate the door may enhance the original affordance and facilitate recognition of the route/door indicated. Occupants who perceive and follow the signs will act in a pre-planned manner; hence the signs effectively reduce valuable occupant decision time in times of emergency. But similar to the example of door in the environment, the effective use of signage is also subject to the process of visual perceiving and cognizing of the signs. As a result, it is not guaranteed that occupants will register seeing the signs and follow the instruction given by the signs.

In summary, direct examination on people's evacuation behaviour and performance in an emergency is apparently hindered by the potential ethical issues and difficulty involved in conducting such an experiment, so data is relatively scarce and ambiguous; besides, existing data collected from indirect examination (e.g. interview) under everyday conditions may not represent the outcome of a real emergency situation. Gibson's concept of 'affordance' provides a theoretical framework for a qualitative analysis of how people perceive and utilise signage. There is still a need of quantification concerning how effective the "correctly" designed signage system is likely to be in practice.

2.1.2.3 Interpretation and Compliance

Given a sign can be seen and an evacuee already perceived the sign *in an emergency*, it needs to determine whether the evacuee will correctly interpret and comply with the information conveyed by the sign.

This aspect of the interaction process relies partly on the design of signs (see Section 2.1.1 and Section 2.2) and partly on how people interpret the current design of sign. How people interpret a sign may be influenced by their background (language, education, training, experience etc.) and the relationship between the sign and the target indicated by the sign [Morley *et al.*, 1997].

The interpretation of the information conveyed by standard safety signs was studied through interview and survey to examine the comprehensibility of these signs. Morley *et al.* [1997] interviewed 1365 air passengers at Schiphol Airport in the Netherlands in two phases to study the comprehensibility of graphical exit signs used in aviation*. Wang *et al.* [2006] compared three designs of exit signs placed in a computer generated virtual building space by examining the preference of 560 university students in China. Benthorn and Frantzich [1999] questioned 64 customers at an IKEA warehouse in Sweden to examine their understanding of the meaning of 6 safety signs. McClintock *et al.* [2001] asked 90 members of the public outside a retail store in the UK to rate 10 graphics symbols which they might associate with their safety in an emergency. The results from all above studies show that the meaning of emergency exit signs are sufficiently understood by the general public since they frequently appear in the daily life. It should be noted that the findings obtained from these studies *under everyday conditions* do not answer the question posed at the beginning of this section.

2.1.3 Modelling the Interaction between Occupants and Signage Systems

One of the important principles in designing a signage system is to identify the primary escape route from each place within the premises [BS 5499-4:2000; ISO 16069:2004]. A series of signs is then successively positioned along this route until a place of safety or a final exit is reached. As the primary escape route normally represents the shortest travel distance leading to a place of safety or the exterior, following this route is equivalent to compliance with the signs provided. Most evacuation models are capable of simulating occupants evacuating via the shortest route. Thus the interaction between occupants and signs is often omitted, i.e. either explicit representation is not necessary when simulated agents follow the shortest route; or the interaction is represented as a 100% rate of compliance with signs when the agents are allowed to detect, interpret and use the signs [Filippidis *et al.,* 2003, 2006; Pan, 2006], which are then assumed to indicate the shortest route.

* The signs used in the research are developed by referring to ISO 3864 and EEC Directive 92/58, so they resemble exit signs used in buildings.

Evacuation models which implement, or claim to include, a representation of signage system include

- ALLSAFE [Heskestad & Meland, 1998],
- BGRAF [Ozel, 1985, 1987, 1988, 1991, 1993],
- buildingEXODUS [Galea *et al.*, 2004; Filippidis *et al.,* 2001, 2003, 2006, 2008; Xie *et al.*, 2007, 2009],
- E-SCAPE [Reisser-Weston, 1996],
- EvacSim [Poon, 1985; Poon & Beck, 1994],
- Legion [Kuligowski & Peacock, 2005],
- MASSEgress [Pan, 2006],
- MOBEDIC(EGRESS) [Doheny & Fraser, 1996],
- PEDROUTE [Buckmann & Leather, 1994; Barton & Leather, 1995; Bulman & Clifford, 1995; PEDROUTE V5 Manual],
- and SGEM [Lo *et al.*, 2000, 2004, 2006].

However, detailed information regarding how signage systems work in a simulation is only found in buildingEXODUS [Galea *et al*., 2004], MASSEgress [Pan, 2006] and PEDROUTE [V5 manual], while the available information about the other models just briefly addresses the function of signage. Therefore, buildingEXODUS, MASSEgress and PEDROUTE along with four other representative models are further described in Section 2.4 (an exclusive section for reviewing evacuation models), while the modelling of signage in ALLSAFE, BGRAF, E-SCAPE, EvacSim, Legion, MOBEDIC, SGEM and other studies of agent-based simulation [Raubal, 2001; Hajibabai *et al.*, 2007] involving signage is briefly introduced in Section 2.4.2.2 based on the information available to the author.

2.2 Guidance on Design and Use of Signage by Legislation and Standards

The wide recognition of the importance of safety signs in public areas and workspaces has seen the development and publication of a series of regulations and national/international standards since the late 1970s. The prescriptions of signage in these codes depict two efforts to improve public safety in buildings. One is to ensure safety signs are provided as a compulsory legal requirement at places where a risk has been identified. The other is to ensure the information conveyed by safety signs is standardised and readily understood.

2.2.1 ISO Standards and EEC Detective

With the continuous growth of international travel, trade and mobility of labour, there has been a great need for a universal communications method for conveying safety information. In the light of this need, the International Standards Organisation (ISO) published the first international standard for health and safety signs, ISO 3864:1984 (Safety colours and safety signs), in 1984 in a bid to create such a universal signage language.

ISO 3864 was technically revised later in 2002, whilst a number of other more specific standards were also published by ISO, including ISO 6309:1987 (Fire protection – Safety signs), ISO 7010:2003 (Graphical symbols – Safety colours and safety signs – Safety signs used in workplaces and public areas) and ISO 16069:2004 (Graphical Symbols – Safety signs –Safety Way Guidance Systems) etc. These international standards have been widely adopted and converted into national standards by many countries.

Europe was faced with the same situation when stronger economic connections between EU community member states highlighted the potential problem caused by a variety of safety signs used across member states. These signs often had different designs of graphical symbols and contained text message in local languages (see Figure 2.1). In order to solve the problem, a similar guideline was adopted by the European Union to form the European Community Safety Signs Directive 92/58/EEC – safety and/or health signs in 1992. The contents of this Directive were required to be written into the national health and safety regulations of every EU member state to standardise safety signs to reduce confusion and bypass the language barrier.

(a) An emergency exit sign installed in the Scandinavian Star [1990]

(b) An emergency exit route sign used in Sweden until December 1995 [Benthorn & Frantzich, 1999]

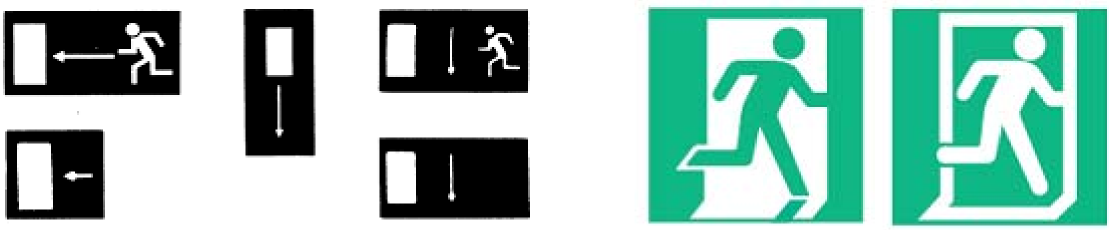
(c) An exit sign seen at Grosvenor House in London, the UK, 21st April 1996 (Photo by Dave Benett)

Figure 2.1: Three different designs of exit signs used in European countries in the 1990s.

2.2.2 British Legislation and Standards

Prior to the introduction of international standards and European directive, exit signs used in the UK were primarily text signs [The Safety Signs Regulations 1980 (SI No. 1471)]; directional arrows were only added along with text where appropriate (see Table 2.1, category 1). In response to the 92/58/EEC Directive, the UK's Health and Safety Executive produced a legal implementation, the Health and Safety (Safety Signs and Signals) Regulations 1996 (SI No. 341), to regulate the design and use of safety signs. The Regulations suggested new design, colour, shape of safety signs (see Table 2.1, category 2), and ceased the use of text only exit signs by the end of 1998.

In the mean time, British Standards Institution (BSI) published BS 5499 series of standards, which are mostly aligned with ISO 3864:1984 and ISO 6309:1987. However, these ISO standards and the 92/58/EEC Directive suggested different designs of graphical symbols for exit signs and exit route signs (see Figure 2.2). As a result, there are currently two types of exit signs used in the UK. While both types are accepted by the current Health and Safety Regulations 1996, exit signs which comply with BS standards are endorsed by ISO standards, thereby potentially achieving better comprehensibility.



(a) the 92/58/EEC Directive (b) BS 5499 series of standards

Figure 2.2: Pictograms suggested by regulations for use in the design of exit signs.

In contrast to the text only sign widely used in the past, the ISO technical committee tends to rely on pictograms to improve the delivery of safety message (through design, colour and shape of the signs), whilst text is used as a supplement and even allowed to be omitted (see Figure 2.3). When text is added along with graphics symbol and directional arrow to form a combination sign, upper case is suggested by ISO 3864-1:2002 (see Table 2.1, category 3a). Similarly, BS 5499-1:1990 uses text in upper case for combination exit signs too (see Table 2.1, category 3b).

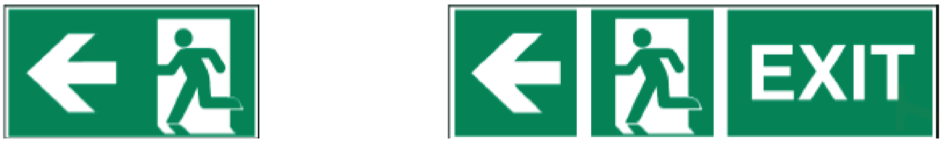


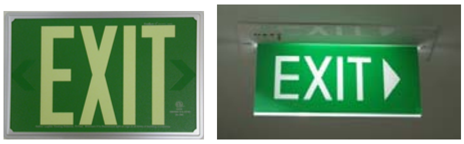
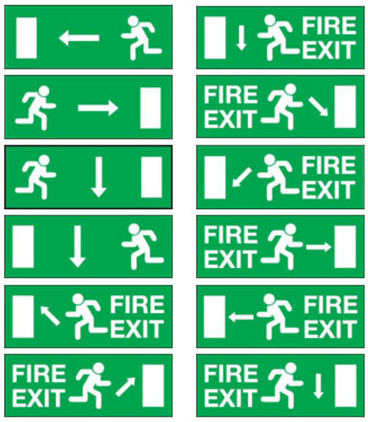
Figure 2.3: Combination exit signs without and with text component in ISO 3864-1:2002.

The importance of text was recognised again in BS 5499-4:2000, which emphasizes the use of supplementary text to assist in the interpretation of escape route signs including exit signs (see Table 2.1, category 4). The BS standard refined the use of text in two aspects. Firstly, apart from the initial letter of the first word, the wording of the supplementary text should be lower case, which is considered to be more comprehensible than upper case. Secondly, “Exit” and “Fire exit” are clearly differentiated (see Figure 2.4). The former should be used with an escape route sign that indicates a path leading to a place of safety, while the latter should be bound with an escape route sign that indicates an alternative path provided specifically to be used in the event of the evacuation of the premises.

Figure 2.4: “Exit” sign and “Fire exit” sign in BS 5499-4:2000.

Given the brief introduction of the history of exit signs used in the UK, the BS5499 signs were used in this study. In addition, resolving text component was selected as the criteria to assess the visibility of sign.

Table 2.1: Exit signs and fire exit signs previously used and currently in use in the UK.

Category	Legislation and Standards	Example of Exit Signs and Fire Exit Signs
1	The Safety Signs Regulations 1980 (SI No. 1471)	
2	Directive 92/58/EEC - safety and/or health signs The Health and Safety (Safety Signs and Signals) Regulations 1996 (SI No.341)	
3	ISO 3864-1:2002 Graphical symbols -- Safety colours and safety signs -- Part 1: Design principles for safety signs in workplaces and public areas BS 5499-1:1990 Fire safety signs, notices and graphic symbols. Specification for fire safety signs	 (a)  (b)
4	BS 5499-1:2002 Graphical symbols and signs —Safety signs, including fire safety signs BS 5499-4:2000 Safety signs, including fire safety signs	

2.2.3 Effectively Using Safety Signs

2.2.3.1 Viewing Range of the Signs

One important factor for effectively using safety signs is the viewing range of signs, i.e. when placing a sign in a building, the first question need to be solved is:

What is the physical extent within which it is possible to detect and resolve the sign?

(Question 2.1)

The viewing range is often prescribed as the maximum viewing distance in legislation and standards [ISO3864-1:2002, BS 5266-7:1999, BS5499-1:2002, BS5499-4:2000]. The definition of the maximum viewing distance, *D*, is based on a statistical measurement of the ability of the human eye to reliably resolve the critical detail of the safety sign under certain conditions (see Figure 2.5). This measurement is determined by the angular resolution of the human eye and the size of the detail to be resolved on the sign, whilst it is also influenced by the colour, contrast of the sign, the illumination on the sign (externally illuminated sign) or the luminance of the sign (internally illuminated sign) and the present of smoke [Jin 1978, 1985, 1997, 2008] between the observer and the sign.

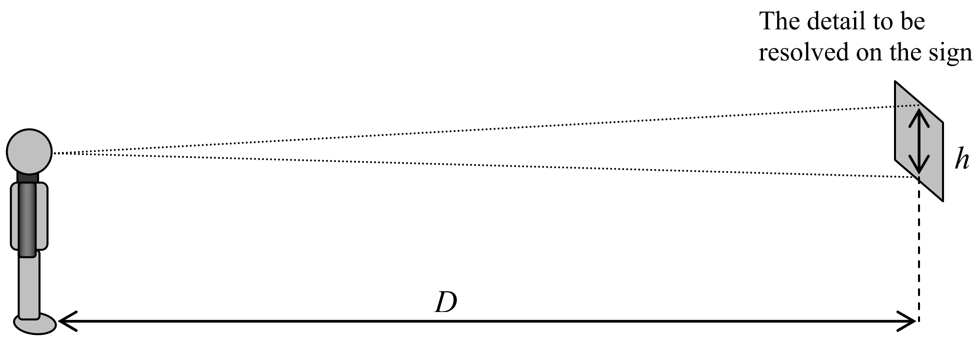


Figure 2.5: The maximum viewing distance of the sign.

In current legislation and standards [ISO3864-1:2002, BS 5266-7:1999, BS5499-1:2002, BS5499-4:2000], *D* is often conveniently given by Equation 2.1, in which *h* is the height (often in metre) of the critical detail on the sign and *Z* is called the distance factor. The question of "how far away can a sign reliably be seen?" is then turned into (1) to measure the height of the detail to be resolved and (2) select a correct distance factor that reflects the influence of all the other factors considered. However, this simple equation does not fully address Question 2.1 for the following reasons.

$$D = Z \cdot h \qquad \textbf{(Equation 2.1)}$$

The legislation and standards do not have a consistent view on Equation 2.1. The diverse description of the equation lies in three aspects. Firstly, the design of safety signs, including the format of text messages and graphical symbols, has changed along with the evolvement of the legislation and standards (see Section 2.2.2). Secondly, different elements of the sign were selected to represent the critical detail need to be resolved for reliably seeing the sign. Finally, when introducing the distance factor, different levels of consideration were given to the influencing factors.

In the past when text only exit signs were used, a simple rule was set by the Guidance to the Fire Precautions Act to determine the maximum viewing distance of signs [Creak, 1997]. That is letters on signs should be 100 mm in height to be safely read within 25 metres. This is based on the fact that the naked human eye with normal or corrected to normal vision can resolve a small detail that has an angular span of 1 minute, whilst a safety factor of 2 was also introduced to ensure that most people with lower than average visual acuity can still read the signs. In this case, h is the height of the upper case letters (in metre), while Z is given a fixed value of 250, regardless of the other conditions.

The movement towards using graphical symbols to deliver a message influenced the way of defining the maximum viewing distance of signs in both ISO standards and BS standards [ISO 3864-1:2002; BS 5499-1:2002; BS 5499-4:2000]. In ISO 3864-1:2002, h is defined as the height of the sign excluding white border (see Figure 2.6), while the selection of the distance factor Z takes into account the size of the critical detail, the luminance of the sign and its contrast against the surroundings. In practice, ISO 3864 suggests that the factor Z is equal to 100 for illuminated signs (a minimum incident illuminance of 50 lx on the sign surface is required); while it is doubled for internally illuminated signs (an average luminance of the contrast colour greater than 500 cd/m^2 is required).

Figure 2.6: The definition of the height of the sign in ISO 3864-1:2002.

The BS standards segregate the prescriptions of the maximum viewing distance for escape route signs and the other safety signs. For safety signs other than escape route signs*, BS 5499-1:2002 provides similar recommendations as in ISO 3864-1:2002, i.e. h is the height of the sign without the white border, and Z is equal to 120 for externally illuminated signs with a minimum vertical illuminance of 50 lx at the sign. BS 5499-1:2002 also adds that for text only signs, Z should be equal to 225.

The recommendations of the maximum viewing distance for escape route signs are prescribed in BS 5499-4:2000, in which h is defined as the height of the graphical symbol (see Figure 2.7). When recommending distance factor Z, BS 5499-4 takes account of the vertical illumination on an externally illuminated sign or luminance in the case of an internally illuminated sign. Two series of distance factors are provided along with ascending vertical illumination and mean luminance of white contrast colour respectively for these two types of signs. As a complementary to the distance factors in normal conditions, Z is given 100 and 200 respectively in BS 5266-7:1999 under emergency lighting conforming to BS 5266-1:2005 (replaces BS 5266-1:1999) in the mains-failure condition, whilst h is rolled back to its previous definition as the height of the sign.

Figure 2.7: The definition of the height of the graphical symbol in BS 5499-4:2000.

It should be noted that the BS standards emphasize that the prescriptions of the distance factor take account of the need to resolve and comprehend the graphical symbol on the sign, whilst the supplementary text is not even required to be legible at the maximum viewing distance [BS 5499-1:2002].

The method of applying a single maximum distance value to assess the viewing range of signs is widely used following the prescriptions in these legislation and standards. Despite the conciseness of Equation 2.1 suggested by these standards, there are different views on

* This category of safety signs are generally not required to be self-luminous or internally illuminated.

selecting the critical detail on the sign to be resolved and different considerations when coming up with a distance factor (see Table 2.2). In addition, this method omits two important factors: the angular distortion (see discussion in Section 4.2 of Chapter 4) and smoke (see discussion in Section 2.3 and Section 10.1 of Chapter 10), both of which may influence the actual extent within which it is possible to see and read the sign. In summary, neither does this method provide a satisfying answer to Question 2.1 posed at the beginning, nor does it explicitly describe the viewing range of signs.

Table 2.2: Distance factor Z for safety sign in legislation and standards.

Legislation and standards	**Definition of *h***	**Distance factor and applicable conditions**
Legacy Fire Precautions Act and BS 5499 (for escape route signs)	Height of letters (uppercase) on the sign	Z=250, a safety factor of 2 is included.
ISO 3864-1:2002 (for all safety signs)	Height of the sign excluding white border	*Z*=100 for illuminated signs (a minimum incident illuminance of 50 lx on the sign surface is required); Z=200 for internally illuminated signs (an average luminance of the contrast colour greater than 500 cd/m^2 is required).
BS 5499-1:2002 (for safety signs other than escape route signs)	Height of the sign excluding white border	Z=120 for externally illuminated signs with a minimum vertical illuminance of 50 lx at the sign; Z=225 for text only signs.
BS 5499-4:2000 (for escape route signs)	Height of the graphical symbol	For externally illuminated signs: Z=95, Vertical illuminance at sign ≥ 5 lux Z=170, Vertical illuminance at sign ≥ 100 lux Z=185, Vertical illuminance at sign ≥ 200 lux Z=200, Vertical illuminance at sign ≥ 400 lux For internally illuminated signs: Z=150, Mean luminance of white contrast colour≥ 10.0 cd/m^2 Z=175, Mean luminance of white contrast colour≥ 30.0 cd/m^2 Z=200, Mean luminance of white contrast colour≥ 100.0 cd/m^2 Z=215, Mean luminance of white contrast colour≥ 200.0 cd/m^2 Z=230, Mean luminance of white contrast colour≥ 500.0 cd/m^2
BS 5266-7:1999 (for escape route signs)	Height of the sign excluding white border	Z=100 for externally illuminated signs Z=200 for internally illuminated signs in the mains-failure condition.

2.2.3.2 Using Signs in Buildings

The provision of safety signs in premises is based on the assumption that some of the occupants may be unfamiliar with the complex building structure [BS 5499-4:2000]. Therefore, they need assistance in finding a way leading them to a final exit or a place of safety in times of emergency, especially if there is an absence of security staff or experienced companions. Even for those who are familiar with the building, signs are still required for indicating alternative exits, because it is recognised that

> "*People usually leave premises by the same way that they enter or by routes which are familiar to them*" [the Health and Safety (Safety Signs and Signals) Regulations 1996].

However, these routes may not be the shortest ones, and they may be congested if many occupants try to use them or inaccessible due to the presence of hazards in the event of an emergency evacuation. These situations suggest that an effective use of emergency signage is essentially the goal to be pursued by the provision of safety signs.

Whereas good practice in signage system design can be assured by following the criteria set out by the current legislation and standards in force, effectively using signs in buildings is only addressed by relatively general principles about application and positioning of signs [the Health and Safety (Safety Signs and Signals) Regulations 1996; BS 5499-4:2000; ISO 16069:2004]. BS 5499-4:2000 for instance, makes recommendations that address selection of the appropriate type of sign, the location of signs, mounting positions, lighting and maintenance. Despite these measures designed to ensure that a sign is provided where appropriate and is clearly visible, no information and test method are provided as to how occupants perceive, interpret and follow the information conveyed by the sign.

2.3 The Influence of Smoke during an Evacuation

2.3.1 Evaluation of the Influence of Smoke upon People Discerning Exit Signs - Theoretical Basis and Empirical Research

The ability of people to perceive and follow information from signage during an evacuation from a fire is often impaired by the presence of smoke due to the visual obscuration effect and irritant effect [Jin 1978, 1997, 2008; Jin & Yamada, 1985; Rea *et al.*, 1985; Collins *et al.*, 1992; Wong & Lo, 2007; Zhang & Rubini, 2009, 2010]. In theory, the visual obscuration effect of smoke comes from two forms of impact. Firstly, the direct luminous fluxes from the exit signs are scattered by the smoke particles, effectively reducing the intensity. Secondly, the ambient luminous fluxes that are also scattered by the smoke particles are superimposed on the fluxes of exit signs, effectively reducing the contrast between the exit signs and the background, so that it becomes difficult to distinguish the signs from the background. In addition, smoke can irritate the surface of the eye, and effectively makes the observer unable to open their eyes for a long time, hence reducing their ability to focus on and resolve the signs.

There are two approaches to estimate the influence of smoke upon visibility. The first approach [Husted *et al.*, 2004; Ewer *et al.*, 2007] used optical density (*OD*), which by definition is an expression of the transmittance of the light through smoke, i.e.

$$OD = -\log_{10}\frac{I}{I_0},$$ **(Equation 2.2)**

where I is the intensity of light passed through smoke and I_0 is the intensity of incident light (see Figure 2.8). Since OD is also related to the measurement of the smoke density, this approach is able to estimate the decrease of the intensity of light after it passes through a certain distance through the smoke. This approach addresses the first form of interference, i.e. the influence of smoke concentrations and the distance the light transmitted through smoke, yet it does not take the second form of interference into account.

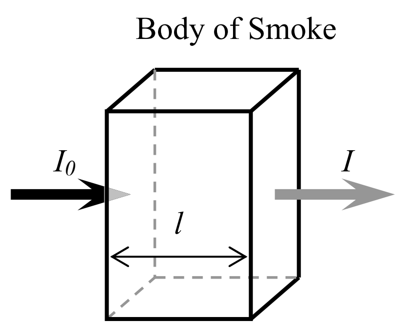


Figure 2.8: Incident light passes through a body of smoke.

The second approach is based on the definition of visibility through contrast threshold [Jin, 1978, 2008; Sychta, 1997; Zhang & Rubini; 2009]. A frequently used definition of the visibility of an object is the distance by which the contrast between the brightness of the object and that of the background is reduced to a threshold value [Jin, 1978, 1997, 2008; Jin & Yamada, 1985]. The contrast, C, measured by the luminance intensity of the object, B, and the luminance intensity of the background, B_0, is defined as

$$C = \left|\frac{B}{B_0} - 1\right|.$$ **(Equation 2.3)**

The value of the obscuration threshold contrast is often used as 0.02 [Jin, 2008]. To evaluate the visibility of exit signs in smoke a viable method is to measure the contrast C with a photometer, while psychophysical tests were also carried out to measure the obscuration/legible threshold distance at which the signs are detectable/readable through the smoke [Jin, 1978, 1997; Jin & Yamada, 1985; Rea *et al.*, 1985; Collins *et al.*, 1992; Wang & Lo, 2007; Zhang & Rubini, 2009, 2010].

Jin [1978, 1997] found, through the experimental study of the impact of fire smoke on signage visibility conducted in Japan, that human visibility levels at both the obscuration threshold of the exit sign and the legible threshold of text on the sign are impaired as the smoke density increases. He concluded that the influence of smoke upon visibility can be expressed as a constant product of the visibility distance and the smoke density (measured in the unit of extinction coefficient) in the signage visibility range between 5 m and 15 m. See Equation 2.4,

$$V \cdot C_s = K\,, \qquad \textbf{(Equation 2.4)}$$

where V is the visibility of the sign at the obscuration threshold, C_s is the extinction coefficient of the evenly mixed smoke and K is the constant obtained from the tests of subjects viewing the exit signs through smoke. The value of K only varies with the type of sign and individual visual acuity. For example, for a light-emitting sign, K=8 (5~10); while for a light-reflecting sign, K=3 (2~4). Jin's work is frequently cited in the fire safety community given the data collected. His empirical model is used in fire protection engineering [Jin, 2008]. However, the size of the sign was not described in Jin's study, and his empirical equation mostly takes account of homogeneous smoke.

Zhang and Rubini [2009] argued that the contrast perceived by the viewer varies with the time of observation and the viewer's location. They also suggested that it is better to assess the visibility of exit signs in smoke by focusing on how discernable are the signs. To support their argument, they proposed a new method of assessing the signage visibility in smoke through the concept of image based visibility. They redefined the contrast based on the image of the sign as

$$C = \frac{\Delta L(t,x)}{L_{mean}(t,x)}\,, \qquad \textbf{(Equation 2.5)}$$

where $\Delta L(t,x)$ and $L_{mean}(t,x)$, as a function of time (t) and location (x), are the standard deviation and the mean value of the pixel intensity of the image. Zhang and Rubini [2007, 2009, 2010] developed a numerical simulation tool to reproduce the synthetic image of the sign at the location of observation by solving the transport equation of radiation. They validated the model prediction of the visibility of the sign by comparing against the experimental data on light extinction collected in a laboratory scale smoke test tunnel. Through this method, a Floor Map of Visibility [Zhang & Rubini, 2009, 2010] can be generated for an enclosure according to the distribution of smoke concentrations and the optical properties of the signs. The Map provides a comprehensive estimation of the overall visibility performance of a design.

Zhang and Rubini's method of assessing the visibility of sign in smoke is sophisticated, yet computationally complicated. In Chapter 10, an alternative method which incorporates adapted Jin's model [1978, 1997, 2008] into the calculation of the visual catchment area (VCA) of signage model is introduced to allow the estimation of the impact of smoke upon the visibility of sign in evacuation modelling, taking account of both the size of sign and inhomogeneous smoke distribution.

2.3.2 Experimental Study of the Impact of Smoke on People's Egress Performance and Behaviour

Not only does the presence of smoke influences evacuee's visual perception during an evacuation involving fire, but it also influences their movement and evacuation behaviour due to the physiological and psychological effects to exposure to such dynamic and harmful environmental conditions [Purser, 1996, 2001, 2003, 2008; Gwynne *et al.*, 2001; Proulx & Fahy, 2008; Jin, 1978, 1997; Jin & Yamada, 1985, 1989; Frantzich & Nilsson, 2004; Wright *et al.*, 2001b]. When engulfed in smoke, evacuees may have difficulty in discerning the environment and performing accurate movement; they may demonstrate different patterns of behaviour. Therefore, human performance and behaviour observed in a normal situation can not be applied to predict their performance when exposed to such abnormal conditions. Thus it requires models to correctly represent the interaction between evacuees and smoke in evacuation simulation [Purser, 2003]. Models which incorporate the ability to simulate the impact of fire hazards mostly utilise a Fractional Effective Dose (FED) model developed by Purser [1989, 1995, 2008] and the data collected by Jin [1978, 1985, 1997, 2008] on human behaviour and tenability in smoke. The FED model is relatively complex and requires the user to supply a detailed input of fire hazards; whereas Jin's empirical model deals with smoke only and requires a simple input of smoke concentrations and property (irritant or non-irritant).

Studies on the impact of any fire hazards upon evacuees were hindered by the harmful conditions on human subjects involved, forcing model developers to rely on the results produced by experimental trials conducted under restricted experimental conditions and controls. Three well conducted experimental studies of the impact of smoke on people's movement and behaviour under similar experimental conditions and configuration are described below.

Jin's work

In the 1970s and 1980s, Jin [1978, 1985, 1989, 1997] conducted a series of experimental studies on the impact of smoke on evacuees due to its importance for understanding safe escape from a fire. His work was typical of the early research on evacuation through smoke-filled environments in that human subjects were used in the research and they were exposed to real smoke during the experiments.

To simulate the scenario of evacuees travelling through an actual building fire, Jin [1978, 1997] set up a corridor of 20 metres in length and filled it evenly with smoke produced from separately burning different materials, including wood, polystyrene and polyvinyl chloride etc, to represent irritant smoke and non-irritant smoke in an early state of a fire. The participants were asked to navigate though the corridor or to discern exit signs pre-installed inside, while simultaneously measures were performed to assess the impact of smoke of various densities and irritant levels (i.e. irritant and non-irritant smoke) upon the participants' evacuation behaviour and performance.

Jin [1978, 1997] found through the analysis of the data collected that human visibility levels at both the obscuration threshold of the sign and the legible threshold of the words on the sign were impaired as the smoke density increased. He described this relationship as a constant product of the visibility distance and smoke density (in the unit of extinction coefficient) measured. In addition, Jin produced a relationship between travel speed and smoke density for both non-irritant and irritant respectively based on the empirical data, and he suggested the minimum visibility required for safe escape from smoke environment accordingly.

Wright *et al.*'s work

Smoke can obscure the layout of buildings during an emergency, so lighting systems and wayguidance systems can be especially vital for evacuees trying to search for an exit and escape. In order to compare the efficiency of such systems in guiding evacuees in smoke, Wright *et al.* [2001b] conducted experimental trials to examine and compare people's travel speeds in a smoke-filled built environment which employed different lighting and wayguidance systems separately. The trials were performed in a two storey test facility which included a long corridor of 13 metres in length. Non-toxic white smoke was generated from a mineral-based fluid. The smoke density measured in the corridor during the trials was 2.5/m (OD 1.1 m^{-1}). 18 participants took part in the trials and experienced the same set of 6 scenarios, i.e. five wayguidance systems separately employed and a separate scenario with normal overhead lighting only. According to the travel speeds measured, Wright *et al.* [2001b] concluded that both the emergency overhead lighting system recommended in British Standard BS 5266-1:1999 and the normal lighting system performed worse in facilitating people's progress in smoke than the other wayguidance systems tested. They also suggested the importance and efficiency of the directional visual cues as opposed to increasing illumination.

Frantzich and Nilsson's work

Fire in road tunnels is uniquely characterised by the tunnel structure: evacuation from a tunnel fire is often hindered by smoke due to limited ventilation capacity as well as inadequate lighting conditions. Evacuees embroiled in such circumstance may have to walk significant distances through smoke to find their way out or a temporary shelter, while they may experience reduced visibility and the potential danger of inhalation of smoke and toxic gases. Recent fire disasters including tunnel fires [Voeltzel, 2002] resulted in loss of human lives and stress the need for safety research in tunnel fires.

Frantzich and Nilsson [2004] simulated a smoke-filled tunnel environment and performed evacuation experiments using university students. They aimed at investigating human behaviour in dense smoke and the relationship between smoke density and travel speed. The experiment was performed in a tunnel of 37 metres in length and 5 metres in width. The tunnel was filled with a mixture of artificial smoke and acetic acid to imitate the visual obscuration effect and the irritant effect under a safety allowance. Six cars were put into the tunnel to reproduce a scenario of an accident happened in the road tunnel. The participants with limited information were then asked to walk into the smoke-filled tunnel and make their way out. The smoke density was measured by the light extinction coefficient. The participants were filmed by thermal imaging infrared cameras in order to collect performance data and monitor their behaviour. Five different scenarios were examined varying tunnel lighting conditions, signage and guidance systems employed in the tunnel to indicate the appropriate escape route and the emergency exits. 64 students participated in the experiments on an individual basis, producing the data of travel speeds within a broad range of smoke density.

The results [Frantzich & Nilsson, 2004] confirmed the negative effect of smoke upon the travel speed found previously in Jin's studies [1978, 1997], i.e. the travel speed decreases with the increase of smoke concentrations. The results are important in themselves in that people's travel speeds in relatively dense smoke are measured. It was also found that the participants frequently made use of walls as a navigation aid in dense smoke during the experiment.

Jin's data [1978, 1997] is widely used in evacuation models (such as buildingEXODUS [Galea *et al.*, 2004], FDS+Evac [Korhonen & Hostikka, 2008]) to represent the impact of smoke upon occupant's travel speed and small-scale behaviour. In Jin's experiment [1978, 1997] he examined the effect of smoke with a measured extinction coefficient ranging approximately from 0.5/m to 1.1/m. Thus the models have to introduce assumptions when smoke density is beyond this range in a simulation due to a lack of data. Wright *et al.* [2001b] tested thicker smoke in their experiment which measured 2.5/m. Frantzich and Nilsson [2004] examined the effect of much thicker smoke with the extinction coefficient ranging from 2.0/m to 7.4/m in their comparable research work on evacuee's performance and behaviour in a smoke-filled tunnel. Therefore, there is the prospect of producing a comprehensive representation of the impact of smoke upon occupant's travel speed and behaviour by combining the experimental results obtained from these experiments (see Chapter 11).

2.4 A Review of Evacuation Models and Modelling Signage

The requirement for a better understanding of occupant behaviour in emergency and its impact upon evacuation has been driven by the safety concerns of the public in buildings during an emergency; hence, there is a need in related research fields as well as fire safety engineering for a practical method, which can facilitate safety design in buildings, predict potential dangers arising under extreme conditions, help plan emergency response and sometimes, reconstruct disasters to analyse the underlying causes. Following the progress in the studies of pedestrian and evacuation dynamics [Fruin, 1971; Predtechenskii & Milinkskii 1975, 1978; Wood, 1972; Bryan, 1977; Canter & Matthews, 1976, Canter, 1980; Pauls, 1984, 1990] and computer modelling techniques, a number of computer simulation models have been developed over the past four decades [Gwynne *et al.*, 1999b; Kuligowski, 2008]. These models have become widely used as alternative methods to fulfil the above purposes.

To date there have been more than 60 models (http://www.EvacMod.net) available world wide for research and applications in fire safety engineering. It is beyond the scope of this chapter to describe every model; instead, seven representative models have been selected for review to show the scope and nature of evacuation models, with the emphasis on the representation of occupant wayfinding, occupant interaction with signage, the impact of smoke and in addition, the limitations of the modelling approaches to date.

2.4.1 Evolution of Evacuation Models and Techniques Used in Evacuation Modelling

The modelling approach is a virtual representation of a real-world system based on the theory and data gathered, and it is used to simulate the development of the system according to pre-defined rules. For building evacuation models, the real-world system includes the building, occupant population and the scenario. The primary goal of modelling an evacuation is to approximate the simulated scenario and produce results that are close to the outcomes in reality had such an evacuation happened under the conditions similar to the simulation settings. In order to achieve this goal, it is essential that as many influential aspects of the real-world system as possible are accurately represented in the modelling and simulation process. As there is no accepted standard approach to achieve this goal, existing evacuation models vary greatly in general structure, function and capability due to the different methodologies adopted. This variation is also due to the difference in the techniques available at the time of model development, the purposes of the models, the understanding of the influencing factors involved in evacuations, the general structure of the model and finally, the efforts developers devoted to the development of models.

Several reviews [Gwynne *et al.*, 1999b; Olenick & Carpenter, 2003; Santos, 2004; Kuligowski & Peacock, 2005; Kuligowski, 2008] have been conducted to improve the understanding of the capabilities of current models and the modelling approaches used. Gwynne *et al.* [1999b] reviewed 22 models and suggested that evacuation models can be categorised by the methodologies used, including three principle approaches (*optimization*, *simulation* and *risk assessment*) and a further breakdown of the means of representing three essential aspects of evacuation modelling (*building enclosure*, *occupant population* and *occupant behaviour*) within these principle approaches. For the models available at the time of review, two methods of representing building enclosure i.e. *fine network* and *coarse network*, and two methods of representing the population i.e. *individual* and *global perspective*, were identified respectively. With the development of modelling methodologies, a third method of representing building enclosure, namely *continuous network*, was also identified [Kuligowski & Peacock, 2005]. This continuous approach was used more frequently in recent models (such as SIMULEX [Thompson, 1994; Thompson & Marchant, 1994, 1995a, 1995b, 1996], FDS+Evac [Korhonen & Hostikka, 2008] and MASSEgress [Pan, 2006]).

The coarse node approach (e.g. EVACNET4/EVACNET+ and PEDROUTE) models a building as an abstract network which consists of connected nodes. Each node, representing an entire or part of a building component (e.g. a room), is the unit used to track occupant location and transition. The fine network approach (e.g. STEPS, EGRESS and buildingEXODUS) models the building enclosure as a cluster of small uniform nodes. Each node covers a small area which normally accommodates one occupant. Each occupant occupies a node at one time and their movement is simulated as a series of small steps in the nodal network. Compared with the coarse network approach which tracks occupant location and transition between rooms, the fine network approaches can track occupant location and transition between smaller unit of space and offer the flexibility required to model complex occupant movement, interaction and behaviour. The continuous approach (e.g. SIMULEX, FDS+Evac and MASSEgress) is somewhat similar to the fine network approach, but it tracks occupant location with a coordinate system and offers the additional flexibility required when implementing occupant behaviours which may be sensitive to occupant location, orientation and inter-occupant distance.

From coarse and fine networks to a continuous network, the representation of building enclosures and objects increase in resolution. While all three approaches have been adopted by various modelling attempts and implemented along with corresponding methods of representing occupant population and occupant behaviour, it is important to note that the means of representing building enclosure and occupant population greatly influenced the behavioural perspective of these models [Gwynne *et al.*, 1999b; Gwynne, 2000]. Since the interest of this research of occupant interaction with signage falls into the behavioural perspective, the analysis and description of the seven selected models is organised according to the approach adopted for representing building enclosure. These three approaches along with the selected models in each category are described in the follow sections.

2.4.1.1 The Coarse Network Approach

The coarse network approach converts a building into a network of nodes, where each node typically represents a single unit of building component such as a room, a hall, a flight of stairs and a lobby etc. In some cases, a building component can be broken into several nodes or several building components can be merged into one node through user interaction. There is no precise representation of occupant location inside nodes due to the nature of the coarse node network; their locations inside the building are tracked by the relative location of nodes in the network. The nodes are connected by arcs based on the connectivity of these building components and the capacity of the connections to form a network description of the building. To complete the network model the user needs to specify the capacity of each node, the time it requires to move occupants from one node to another via each arc (i.e. the traversal time) and the flow capacity. Occupant movement is simulated as leaping from one node to the other following the links which determine both the connectivity and transmission rate between nodes.

The coarse network approach is mainly used by those models developed in the 1970s and 1980s when computers have relatively small amount of memory and less processing power. This approach is the least computationally expensive. The great efficiency of memory and CPU usage of the coarse network approach is at the sacrifice of the simulation details inside the building components, such as occupant location, individual movement and the interaction with both the other occupants and some building features, such as obstacles [Gwynne *et al.*, 1999b].

Typical coarse network models include ALLSAFE [Heskestad *et al.*, 1998], EESCAPE [Kendik, 1986], E-SCAPE [Reisser-Weston, 1996], EVACNET+/EVACNET4 [Francis & Saunders, 1979; Kisko *et al.*, 1985, 1986, 1998], EXITT [Levin, 1989], PEDROUTE [Buckmann & Leather, 1994; Barton & Leather, 1995; Bulman & Clifford, 1995; PEDROUTE V5 Manual] and WAYOUT [Shestopal, 2003] etc. In the following section, two coarse network models are selected and described. EVACNET+/EVACNET4, as a typical coarse network model, is selected for its simplicity; while PEDROUTE is selected for its advanced development and features that show the trend of model evolvement.

EVACNET+/ EVACNET4

EVACNET+ [Francis et al., 1979; Kisko *et al.*, 1985, 1986, 1998] is a building evacuation program originally developed by Francis and Kisko at the University of Florida in 1984. Since EVACNET+ was limited by 16-bit operating system, it was upgraded to 32-bit EVACNET4 later to be able to handle larger and more complex buildings. They are principally the same model; hence they are referred as the EVACNET model in the following context.

EVACNET accepts a network input of a building representation [Kisko *et al.*, 1985, 1986, 1998]. This network is composed of nodes converted from the building components (rooms, halls, lobbies, stairs etc.) and arcs converted from the passageways connecting these components. To complete the model, the user needs to supply node and arc capacities as well as initial number of occupants within the building. It is recommended that other researcher's empirical results and data are used to help determine these parameters required by the model. Finally, a graphical illustration of the network representation of the modelled building can be manually drawn by following the user's guide. This graphical illustration can facilitate the construction of computer simulation and help understanding of the simulation results produced.

Once the network representation is established, EVACNET runs a simulation of evacuation scenarios to determine the optimal evacuation plan [Kisko *et al.*, 1985, 1986, 1998]. This is achieved by executing an advanced capacitated network flow transhipment algorithm. During this process, the EVACNET model does not represent occupant awareness of the structure, nor allow individual route choice. Instead, it uses a global viewpoint to plan the best possible route for all occupants. The developers pointed out that the results produced from the execution of the model may be different from those of an actual evacuation, because

"*In an actual evacuation individuals independently attempt to achieve an optimum.*"
[Kisko *et al.*, 1998]

Therefore, the aim of using the model is to produce an optimal evacuation plan for occupant training.

The EVACNET model is one of the early attempts to combine empirical study and computer simulation in evacuation studies. The data from empirical study and observation provide a basis for the model to properly represent occupant movement (walking speeds and queuing level etc) in the model, while the computer simulation enables the model to solve problems of the other different and often larger scale buildings.

As an early computer model, the capacity of the EVACNET model is restricted by the available computer power. The model also lacks continuous effort from the developers to improve it. As a result, the usability of this model is limited. This does not necessarily mean a coarse model is too simple to conduct complex simulation. In the next section, a more sophisticated model base on the coarse network approach is discussed.

PEDROUTE

PEDROUTE [Buckmann & Leather, 1994; Barton & Leather, 1995; Bulman & Clifford, 1995; PEDROUTE V5 Manual] is a pedestrian simulation suite developed by Halcrow and London Underground Limited in response to Kings Cross fire in 1987. The model has been continuously enhanced ever since then. The following description of the model is based on PEDROUTE version 5 [PEDROUTE v5 manual].

Like the other models based on the coarse network approach, the PEDROUTE model converts the building in question into a coarse network representation. The network is composed of blocks which are defined and manually drawn by the user using an interactive tool called Network Builder. Normally a block has the shape of a rectangular polygon, but a non-rectangular polygon is also allowed. The block can cover the area of a building component; however, a building component can be manually segregated into multiple blocks to allow a more detailed occupant flow inside the component to be examined. According to the different functions of building component, the blocks are categorised into several types, including passage way, concourse, junction, lift, stairs, escalator and user defined types. Also included are moving walkway, UTS gate and platform that are exclusively for modelling stations. Adjacent blocks are often connected by 1-way or 2-way links to represent the viable route between them and the constraints exerted upon the occupant flow.

Since version 4 of the PEDROUTE model the occupants have been modelled as individuals. However, the occupants can only be tracked in blocks due to the way in which the building is represented. The occupants can move from one block to another via the link that connects two blocks. The movement of occupant flow is determined by the function [PEDROUTE v5 manual]

$$Flow = \frac{Number\ of\ People}{Traversal\ Time}, \qquad \textbf{(Equation 2.6)}$$

where *Traversal Time* is a function of occupant density in the block.

The PEDROUTE model was originally developed to simulate the circulation of commuters in stations. In a normal situation, the occupants always travel along the routes from where they enter the station to the destinations which have been assigned to them prior to the simulation. PEDROUTE is also capable of simulating evacuation of some parts or the entire station in an abnormal situation. When simulating an evacuation, PEDROUTE executes a dynamic assignment algorithm to assess the quickest way of moving the affected occupants out of the station and assign the new routes to them accordingly. Not only does this algorithm consider the shortest route available, but also the congestions built up in the station. Therefore, it can redirect occupants to avoid being trapped by potential bottlenecks.

Apart from the movement controlled by the route assignment algorithm from a global viewpoint, the PEDROUTE model also include five subtle model refinements: signpost, activity, closure, platform alternative and exit-proportions-by-destination, or crossover. These refinements introduce a new method into the model that simulates occupant interaction with the physical environment and the consequent impact upon their local movement and behaviour.

The introduction of signposts in the PEDROUTE model is based on the consideration that people would look for 'Exit' signs or similar wayfinding clue during circulation and evacuation [PEDROUTE v5 manual]. In the actual implementation of this behaviour, signposts are added as a complementary wayfinding feature, which allow the user to manually control some or all agents to move in a certain direction, often represented by the link connecting two blocks, towards a selected destination. The signpost implicitly simulates the process of occupant 'seeing' a sign and then following a particular route indicated by the sign in the building. The signpost has three main properties. The first property, destination, determines who will be affected by the signpost; they are those who are originally heading for this particular destination. The second property defines how the occupant flow would split and use multiple routes if everyone follows the sign. The last property defines a list of links which will be followed by those who are affected by the sign. The developers realised that not all people would see and use the signs in reality; hence, a global compliance probability, SPRO, is defined accordingly to represent the degree of compliance or observance in the interaction between occupants and signs.

Compared with EVACNET, PEDROUTE has two novel features that reflect the trend of the development of evacuation modelling. Firstly, the occupants are treated as individuals. This would then allow different attributes to be applied to individuals. This development facilitates simulating an individual as a unique entity and studying the emerging phenomena from the individual's interaction with the other occupants and the environment. Secondly, the model introduced the representation of occupant local behaviour as response to the interaction with the physical environment. This is among the early attempts to treat the occupants simulated as adaptive persons rather than unified occupant flows. However, due to the inherent limit of the coarse network approach, the PEDROUTE model can not fully develop the two features in modelling and benefit from them. For instance, it is difficult to precisely define signage visibility and simulate the interaction process with signage. In the next section, these two features are more clearly demonstrated by three selected fine network models.

2.4.1.2 The Fine Network Approach

The requirement for a better understanding of occupant movement, behaviour and interaction in an evacuation has lead researchers to seek a better modelling method to address the configurational, environmental, behavioural and procedural aspects of evacuation [Thompson 1994; Thompson & Marchant, 1995; Owen *et al.*, 1996, 1997; Galea *et al.*, 1996a, 1996b; Gwynne *et al.*, 2000, Filippidis *et al.*, 2003, 2006, 2008]. Meanwhile, contemporaneous development of computational power and computer simulation methods facilitated the design and implementation of more complex evacuation models and eventually, led to the development of fine network models such as STEPS [Hoffmann & Henson, 1997; Wall & Waterson 2002]. A common feature of the fine network models is an improved tracking of occupant location based on a fine network representation of building space. This feature allows detailed calculation of individual movement and interaction.

The fine network approach models a building component as a cluster of small (often square) uniform nodes. Each node corresponds to a small physical area in the enclosure and is often set to the size required to accommodate one standing adult, e.g. 0.5×0.5 m. The nodes are connected by arcs to represent their connectivity as well as viable travelling directions for occupants. Since a building component may be modelled by hundreds and thousands of nodes, this approach requires a substantially greater amount of computer memory and CPU time in simulation than the coarse network approach does, but the fine network approach is superior in the following major aspects nevertheless.

Firstly, the fine network approach can represent occupant orientation and location within a building component and track their movement, therefore opening up the potential for simulating the interaction with signage (the coarse network approach can not determine occupant location inside a container node, therefore it can not represent influencing factors such as the relative distance and orientation between occupants and signs). This approach models occupants as individual entities. Each individual occupies a node at a time and may transfer to another unoccupied node according to certain movement rules at a successive time step. The location of each occupant can be denoted by the coordinates of the node they engage. In addition, a full record of an occupant's movement can be produced by attaching time stamps to their positions during the simulation.

Secondly, the fine node network can be used to store information required to simulate occupant global and local behaviour. Occupants normally have direct access to surrounding nodes; therefore, they can perceive information in these nodes and respond accordingly. For instance, the global occupant behaviour can be readily modelled and simulated by distributing pre-computed wayfinding information to the nodes [Thompson & Marchant, 1995a; Keßel *et al.*, 2002; Ketchell, 2002]. The occupant global behaviour reflects an occupant's ultimate goal and the strategy employed to achieve this goal. In general, occupants are motivated to escape from the premises via either the shortest route or a selected route based on their familiarity with the building structure. In either case, an awareness of the locations of viable exits is essential for occupants to compare exit distances, make a choice of exit and find the proper way leading to a desired exit. This would require a complicated and sophisticated method to represent the structural awareness. This requirement, however, can be fulfilled in a more convenient way through the potential/distance map based on the fine network representation of building. The potential/distance map is a pre-computed map system which is utilised to determine the difference in potential* and/or physical distance from any point inside the building to an exit or location. The simulated occupants only need to check the potential/distance value of the nodes immediately around them to decide the travelling direction for next step. They are expected to reach a target location or an exit leading to the outside by following the map systems, i.e. lowering the potential and/or reducing the distance step by step. With this method, they do not have to possess a global view of the structure or a long range sight to be able to navigate in the building. Although a similar method can be implemented in coarse network models [Kisko *et al.*, 1998] and continuous models

* The potential of a node is a measure of distance between the node and the nearest exit. An example of creating a potential map is given in page 48, Section 2.4.1.2.

[Thompson & Marchant, 1995a; Korhonen *et al.*, 2005, 2007, 2008; Korhonen, 2007], it is the most natural way of implementing map systems in models based on the fine network approach.

The potential/distance map systems based on a fine network solved the complex problem of representing occupant spatial awareness of building structure. On the other hand, this approach is a simplified and overly deterministic solution implemented for the convenience of computer simulation. It captures the general trend of occupants moving towards a nearest exit or minimising the distance to a specific target; however, it is restrictive in two aspects. Firstly, if a map system is not correctly or accurately built, it will result in unrealistic local and/or global movement. Secondly, the simulated occupants behave primarily in a mechanical manner if they simply follow a map system, and it could result in over-optimised performance in terms of individual path selection and under-optimised performance in terms of group behaviour [Gwynne, 2000]. To address these issues, models based on the fine network approach and map system often introduce improvement in two ways:

1. Allow rectification and adjustment made to the distance/potential map.
2. Introduce the ability of occupant perceiving information from the environment and making decisions accordingly.

The first way can improve occupant local behaviour during simulation. There are some cases in which the default distance/potential map may not correctly reproduce occupant local movement. For example, Figure 2.9 shows a segment of a circulation route that is composed of a horizontal corridor connecting a vertical corridor [Galea *et al.*, 2004]. The default distance/potential map will direct occupants to pass the junction from the inner side, since mathematically it is a shorter path than the outer side (see Figure 2.9a). When a large number of occupants try to go through the junction, an unrealistic high density crowd will be formed on the inner side as a result, whilst the outer side will not be equally utilised. In this case, the original distance/potential map needs to be rectified to some extent to reflect the proper usage of the junction (see Figure 2.9b).

(a) The default map system directs most occupants to pass the junction by the inner side.

(b) The rectified map system produces a fair use of the junction.

Figure 2.9: A comparison between the default map system and the rectified map system.

An adjustment can be made to the map system to influence and improve occupant global behaviour during simulation. In most cases a potential map system is automatically calculated from exits to the inside of building enclosure using recursive distance calculation [Thompson & Marchant, 1995a; Keßel *et al.*, 2002; Ketchell, 2002]. Occupant's selection of exit route/exit door refers to this map system and theoretically, it is determined by comparing the physical distance to all known exits to find out the shortest escape route. This algorithm does not take into account occupant's understanding (often dynamic) of the existence and location of exits, their preference in exit selection, the influence of wayfinding cues and environmental conditions. Therefore, the original map system may not correctly reflect the attractiveness of an exit to occupants and their exit route/exit door selection. For instance, a frequently used exit should be effectively more attractive to people than any other less frequently used exits. A commonly used solution [Galea *et al.*, 2004] to address this issue is to adjust the potential map to reflect the difference in attractiveness. If occupants are modelled to travel from location with high potential to location with low potential, an exit which is given a prior consideration will be assigned a lower initial potential value to make it more attractive from a larger area inside the building enclosure.

It should be noted that the application of rectification and adjustment is used to modify the map system prior to a simulation. It does not incorporate dynamic change during a simulation to reflect the impact of changing environmental conditions and wayfinding cues upon occupant exit route/exit door selection, i.e. this method is a 'passive' way to improve the models, since it applies to the distance/potential map to influence occupant movement and behaviour.

The second way is implemented to address the fact that people can receive information from the environment and other occupants and act accordingly. This ability influences individual evacuee's choice of exit and the performance of the evacuating population as a whole. Therefore, it is crucial for the models to represent this ability and subsequent interactions. The occupant-environment and occupant-occupant interactions normally occur within a close distance to those involved. For instance, occupants may try to avoid colliding with obstacles and other occupants [Pan, 2006], redirect from harmful hazards [Gwynne *et al.*, 2001], follow signage [Filippidis *et al.*, 2003, 2006, 2008] and exchange information with other occupants [Owen *et al.*, 1997]. Thus the interactions are often referred as occupant local behaviour as opposed to the global behaviour mentioned previously. The fine network approach allows the occupants to probe the connected nodes within a certain range without the effort of implementing a complex search algorithm. In this way the occupants can perceive information that is necessary for modelling these interactions. In effect, the occupants are given the potential capabilities of 'seeing' and 'feeling' the situation nearby, including the presence of obstacles, hazards, directional cues and other occupants. With the information perceived, the occupant's local response can then be modelled and simulated.

Typical fine network models include BFIRES-II [Stahl, 1982], BGRAF [Ozel, 1985, 1987, 1988, 1991, 1993], buildingEXODUS [Galea *et al.*, 2004; Filippidis *et al.,* 2001, 2003, 2006, 2008; Xie *et al.*, 2007], CRISP [Fraser-Mitchell, 1999], EGRESS [Ketchell *et al.*, 1993; Ketchell, 2002], EvacSim [Poon, 1985; Poon & Beck, 1994], PathFinder [Joe Cappucio, 2000], PedGo [Klüpfel & Meyer-König, 2003], SGEM [Lo *et al.*, 2000, 2004, 2006] and STEPS [Hoffmann & Henson, 1997; Wall & Waterson 2002] etc. In the following section, two representative fine network models, STEPS and EGRESS, are described. The signage model in buildingEXODUS (see Chapter 3) is also described for the purpose of comparison with the other models which implement a representation of signage system.

STEPS

STEPS [Hoffmann & Henson, 1997; Newman & Locke 1998; Rhodes & Hoffmann 2000; Wall & Waterson 2002] (Simulation of Transient Evacuation and Pedestrian movements), developed and maintained by the Simulation Group of Mott MacDonald, is a program aiming to simulate the movement of people under both normal and emergency conditions in buildings. STEPS is based on the fine network approach. It consists of three elements: a fine network representation of the building, a discrete representation of the occupants and an algorithm that dictates the occupant movement in the network. The following discussion mainly focuses on the features of STEPS as an evacuation model.

As the first step of modelling evacuation (and circulation) of occupants in a building, STEPS divides the building spaces on which the occupants can manoeuvre into square nodes. Each node is measured 0.5m×0.5m [STEPS 4.0 User manual], the size that can accommodate one adult occupant. Adjacent nodes are connected by default to allow an occupant to move from one node to another. The entire building is then converted to a network that is composed of hundreds and thousands of nodes. This nodal network is not a physical entity in the building, but rather a virtual grid map of the building that tracks the occupant's location and movement on it. This network is also the basis for the model to implement the occupant movement algorithm.

STEPS treats the occupants inside the building as individuals [STEPS 4.0 User manual]. Each individual has an entity in the model. The entity bears several attributes that characterise the person it represents. The attributes include free walking speed, awareness, patience, association and pre-movement time etc. The free walking speed attribute defines the highest speed an individual can achieve when walking without being hindered by obstacles and the other occupants. The awareness attribute represents the individual's degree of familiarity with the structure of the building. The patience attribute determines if the individual would stay in a queue or redirect to another exit route when entering a crowd condition. The association attribute describes the individual's relationship with other occupants. And finally, the pre-movement time attribute simulates the observed evidence that in case of emergency people may not immediately start to evacuate from the building.

The occupants and the network representation of the building are associated by a one-to-one link between occupants and nodes. Each occupant defined in the model always occupies a node and one node can only accommodate one occupant. The physical movement of the occupant is bounded by the nodal network, i.e. the occupant can only move from one node to a neighbouring node at each step. Figure 2.10 shows an occupant located at a node that is surrounded by eight neighbouring nodes. This occupant can have eight possible movement options as depicted in the figure. Each neighbouring node represents a possible option for travelling at the next time step. The selection of one node from these options is determined by both a potential map system and the occupant movement algorithm.

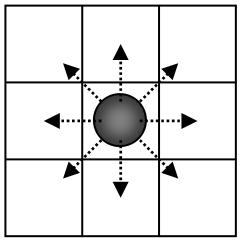


Figure 2.10: An occupant in a 3×3 nodal network and available direction of travel.

The potential map [STEPS 4.0 User manual], which specifies the potential value of each node in the network, is utilised to guide occupants through the building enclosure. The potential value represents the distance from a node to a specific target. Exit, as the final target, is normally assigned 0 potential at the beginning. Then the neighbouring nodes in the horizontal and vertical direction are assigned a potential value by adding the grid size to the current potential; while a neighbouring node in diagonal direction has a potential value by adding $\sqrt{2}$ times the grid size to the current potential. The potential value of all non-exit nodes is calculated in this way recursively. Figure 2.11 shows an example of three iterations of potential calculation on a 3×5m plane (grid size =1m). The node at the top left corner is an exit with initial potential of 0.

	0			

Initial state

1	0	1		
$\sqrt{2}$	1	$\sqrt{2}$		

Loop 1

1	0	1	2	
$\sqrt{2}$	1	$\sqrt{2}$	$1+\sqrt{2}$	
$1+\sqrt{2}$	2	$1+\sqrt{2}$	$2\sqrt{2}$	

Loop 2

1	0	1	2	3
$\sqrt{2}$	1	$\sqrt{2}$	$1+\sqrt{2}$	$2+\sqrt{2}$
$1+\sqrt{2}$	2	$1+\sqrt{2}$	$2\sqrt{2}$	$1+2\sqrt{2}$

Loop 3

Figure 2.11: Calculate the potential values using the recursive algorithm of STEPS. [STEPS 4.0 User manual]

For a building with multiple exits, a target selection algorithm is implemented in the model to simulate occupant decision-making process during an evacuation. This process is based on an assumption that the occupants have a good understanding of the layout of the floor at which they are located. For each known exit on a floor, the algorithm calculates a score for each occupant taking into account the time needed to reach these exits, the potential queuing time, adjustments due to the arrival and leaving of the other occupants and the occupant's patience level. The exit with the lowest score is selected as the occupant's target. Finally the occupant moves to a neighbouring node that lowers the potential value towards this target. This process repeats until the occupant reaches the target.

EGRESS

EGRESS [Ketchell *et al.*, 1993, Ketchell 2002] (Emergency Group Response Evacuation from Structures Study) is a fine network evacuation model developed by AEA Technology since 1991. Starting from looking at the mustering process on offshore installations, the EGRESS model was expanded into a full evacuation model later to be used in the analysis of evacuation from a wide range of buildings. This model is capable of handling very large cases of simulation with many thousands of occupants on plan areas up to a few square kilometres.

Most fine network models like STEPS and buildingEXODUS use a square grid to model the building geometry, whereas the EGRESS model uses a hexagonal grid in particular. The size of the cells is determined according to the minimum area required to accommodate one adult occupant. Given the maximum occupant density of 5 people per square metre used by the model, the default grid spacing, *h*, is about 0.5m (see Figure 2.12).

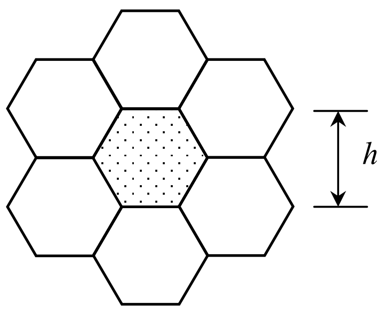


Figure 2.12: An example of hexagonal grid composed of 7 cells.

EGRESS treats the simulated occupants on an individual basis [Ketchell, 2002]. An occupant always occupies a cell in the grid and a cell can only accommodate one occupant at one time.

In general, a non-boundary cell has six neighbouring cells, so the occupant has six available travel directions. When an occupant's desired direction of travel is intersected with the presence of other occupants, the model detects potential collision. The model then either adjusts the occupant's travel speed or temporarily holds the occupant at their current location. The movement of the occupants is then not only affected by their desired travel speed, but also the crowded situation.

As with the grid network, EGRESS includes a map system to guide occupants finding their desired destination. Theoretically, for any cell in the grid there are three states among its neighbouring cells when comparing their distance to a designated target: closer, equal and farther. The occupant, who is heading for a target, only needs to check the state index of these neighbouring cells to decide the travelling direction of next step. Therefore, for every cell in the grid 2-bits of data is enough for the purpose of directional guidance (the fourth state is used to indicate inaccessible wall or obstacle). Starting from the objective cell, the EGRESS model executes a recursive algorithm to assign a route index number to each cell. Compared with the other fine network models (such as STEPS and buildingEXODUS) which use at least an integer number to store the distance or potential value for each cell, the EGRESS model is efficient in memory usage and therefore, it can handle simulation cases with huge geometry.

Figure 2.13 shows an example of such a map system in EGRESS. Cell *A* and *B* at the bottom left corner are two objective cells representing the destination. Three black cells in the middle represent an inaccessible wall. Starting from the cells around the objective, the algorithm recursively assigns route index numbers to all free cells. The cells with three route index numbers are then filled by three different patterns. A few wave-like bands are clearly shown across the hexagonal grid from the bottom left corner to the top right corner. Also shown are two routes selected by two occupants following the map to walk from cell *C* and *D* to cell *A* and *B* respectively.

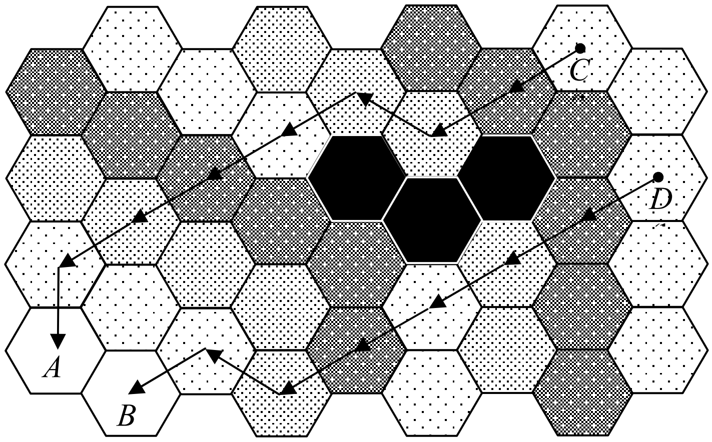


Figure 2.13: An example of the wayfinding map in EGRESS [Ketchell, 2002].

Apart from the default occupant behaviour (i.e. to move to the nearest place of safety via the shortest route available), EGRESS includes a variety of features [Ketchell, 2002] to simulate the other behavioural aspects in an evacuation. These include

- pre-evacuation objective,
- special regions that alter the behaviour of those who cross them,
- sign posting between regions,
- hazard scenario and a method to assess fractional toxic doses received.

The introduction of these features in the EGRESS model reflects the trend that prevailed over the contemporaneous models: the emphasis on the importance of human behaviour and the environmental factors upon an evacuation. Due to the limitation of available documentation, how these features are implemented in EGRESS is unknown. Similar features have been implemented within buildingEXODUS, which are described in detail in Chapter 3.

buildingEXODUS (Signage Sub Model)

The buildingEXODUS (v4.0) model [Galea *et al.*, 2004; Filippidis *et al.,* 2001, 2003, 2006, 2008; Xie *et al.*, 2007] is mainly described in Chapter 3 since it was selected as the platform to implement and demonstrate the new development of the research (Chapter 8). Here the signage sub model in buildingEXODUS is briefly introduced for the purpose of comparison with the other signage model implementations.

The signage sub model addresses both the physical and psychological aspects of the interaction between occupants and signs [Filippidis *et al.*, 2001, 2003, 2006, 2008]. The physical aspect determines the visibility of the signs in the buildings, while the psychological aspect concerns occupants' attentiveness to the signs and their compliance with the signage information. It would be a computing-intensive task to simulate an occupant's visual perception of the environment in real time. Therefore, instead of modelling occupants seeing signs the signage sub model simulates the contact in reverse order, i.e. signs 'see' occupants. A concept of visual catchment area (VCA) [Filippidis *et al.*, 2001, 2003, 2006] was introduced for this purpose to represent the visible range from the sign point of view. In order to determine the extent within which it is possible to see a sign, the model takes account of people's visual acuity (in resolving signs) and the physical factors that might affect an occupant's line of sight. Initially, the prescription of the maximum viewing distance of a sign in relevant legislation and standards (see Section 2.2.3.1) is referred to determine the original extent of the VCA of a sign (see Figure 2.14). Then the average height of occupant, signage mounting height and the height of any obstacle between the occupant and the sign are taken into account to subtract the blind spot from the extent (see Figure 2.15). When the occupant is within the VCA calculated by the above mentioned method, the likelihood of them detecting the signs is assessed. This process takes into account the relative orientation between the occupant and the sign, and the psychological factors. As the signage sub model is still at the development stage, it mainly focused on the physical aspect, while the psychological aspect addressed was primarily based on assumptions due to the lack of data [Filippidis *et al.*, 2003, 2006].

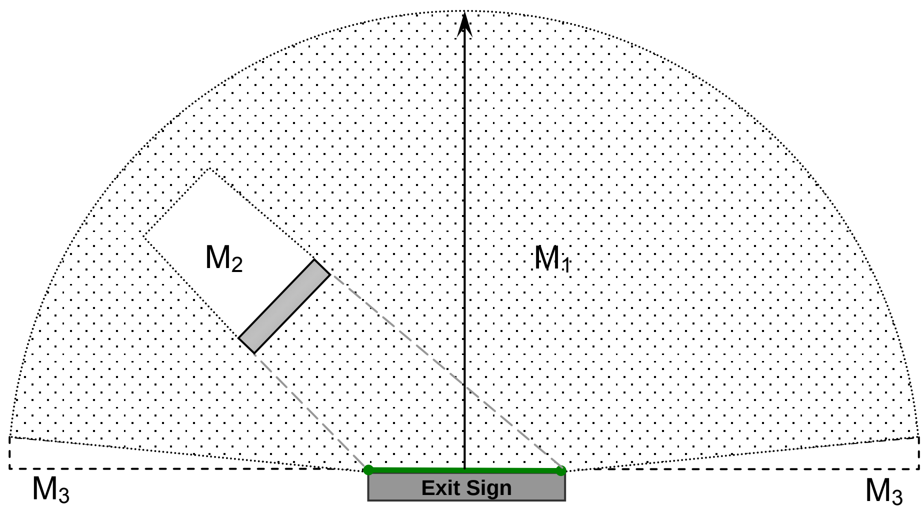


Figure 2.14: The VCA of a sign (M_1).

(M_2 is a blind spot subtracted from the initial VCA due to an obstacle. M3 represents a subtraction of marginal area to reflect the difficulty in resolving the sign in a large angle.)

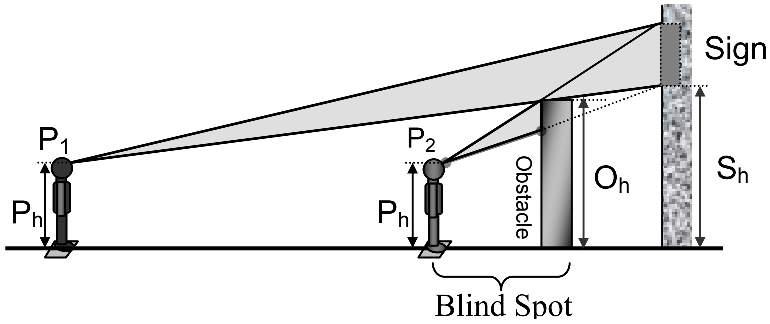


Figure 2.15: A blind spot due to an obstacle standing between viewer P_2 and the sign.

2.4.1.3 The Continuous Approach

The continuous approach, as its name suggests, models a building component as an integral and continuous space. This representation of the building space literally allows an occupant to occupy any point of free space inside the building and face any direction of travel [Thompson & Marchant, 1995a]. Similar to the fine network model, models based on the continuous approach can identify individual occupant location and track their movement towards a desired destination. As their representations of the building space are different, these two approaches are different in modelling of occupant movement and wayfinding in several ways nevertheless.

Firstly, the way in which the building space is represented determines the method of tracing occupants in the building. The fine network models use a pre-generated nodal network to represent the building space; the occupants are traced by the nodal network, i.e. occupants are always associated with the nodes occupied to represent their location. This method of tracing is replaced by a coordinate system in the continuous models. The coordinate system records and traces the occupant location inside a building. Then again, the representation of the building space influences the way in which the occupants travel in the space. In the fine network models the occupants move strictly along the arcs connecting nodes, while there is no such restriction in determining occupant travelling direction in the continuous model.

Secondly, since there is no nodal network to maintain the minimum separation distance between two occupants, the physical space occupied by occupant body has to be defined to avoid occupants intersecting each other. Fruin [1971] defined a ‘body ellipse’ representation based on a large number of human-factors studies of body dimensions. The major diameter of the ellipse represents shoulder breadth and the minor diameter represents body depth (see Figure 2.16a). Another commonly used representation of body [Thompson & Marchant, 1995a; Pan, 2006; Korhonen & Hostikka, 2008] consists of three circles: a circle in the middle representing the main body and two relatively small circles to the left and right side representing the shoulders (see Figure 2.16b).

(a) an ellipse (b) three circles

Figure 2.16: Two representations of human body (view from top).

Finally, although the three examples of continuous models, SIMULEX, FDS+Evac and MASSEgress, implement fine networks in combination with coordination systems, they demonstrate different levels of dependence on fine networks (i.e. being used for different purposes and in different ways). With the typical fine network approach, the information necessary for the occupants finding their desired destination is pre-calculated and represented by the distance/potential map system. Exits associate with the potential/distance map systems that cover the entire geometry. The occupants do not have to possess a global view of the structure to identify the location of a desired destination; instead, they follow the potential/distance map to minimise the distance to the destination step by step. The continuous models are more flexible in implementing the wayfinding strategy. While SIMULEX, FDS+Evac use fine networks in a similar manner (still different from that of fine network models such as STEPS and buildingEXODUS) to this, MASSEgress only uses fine network for collision detection.

Typical continuous models include ASERI [Schneider, 2001, 2003, 2004; Schneider & Könnecke, 2008], FDS+Evac [Korhonen *et al.*, 2005, 2007; Korhonen & Hostikka, 2008], Grid Flow [Bensilum & Purser, 2003], Legion [Kuligowski & Peacock, 2005], MASSEgress [Pan, 2006] and SIMLUEX [Thompson, 1994; Thompson & Marchant, 1994, 1995a, 1995b, 1996; Simulex User Guide 5.8, 2007]. In the following section, three continuous models are selected and discussed, as they use different methods in simulating occupant movement and wayfinding behaviour. SIMLUEX, as an early continuous model, adopts a similar approach as those contemporaneous fine network models, FDS+Evac implements a social force model and MASSEgress implements an occupant movement model based on advanced perception and decision-making concepts.

SIMULEX

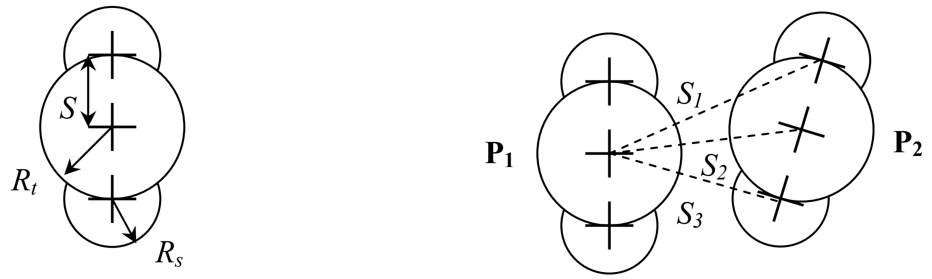
SIMULEX [Thompson, 1994; Thompson & Marchant, 1994, 1995a, 1995b, 1996; Simulex User Guide 5.8, 2007] is an evacuation model developed by Peter Thompson. It was aimed at introducing more accurate and realistic escape movement of individuals into evacuation simulation than what the other contemporaneous evacuation models can produce. This is achieved through two approaches. Firstly, a coordinate system is implemented in SIMULEX to track the location and movement of occupants with higher accuracy. Secondly, observation data is collected and utilised in modelling occupant movement. The aspects of occupant movement modelled in SIMULEX include assessment of optimal travel direction, adjustable travel speed with respect to inter-person distance, overtaking and avoiding direct contact with obstacles.

In SIMULEX, the locations of all stationary and moveable objects are denoted by x and y coordinates. An occupant, as an active entity, also possesses an angle attribute to represent the direction in which they are facing and travelling. Since the coordinates and angle (ranging from 0° to 360°) are stored as floating point values in the program and there is no positional restriction (only bounded by walls and obstacles), literally the occupant can stay at any point of free space in the building and move in a continuous manner in any desired direction. Hence, the model can represent occupant local position, travel direction and travel distance with high accuracy [Thompson & Marchant, 1994, 1995a, 1995b, 1996].

When modelling occupant's evacuation behaviour (i.e. find the route leading to an available exit), the developers adopt a similar approach widely used in fine network models (such as STEPS): the distance map. After defining the building plan by drawing the boundary walls, obstacles and exits, SIMULEX creates a grid network to cover the entire building plan. The grid network is composed of square blocks of the same size. The blocks, measured 0.25×0.25m (0.2×0.2m in a later version [Simulex User Guide 5.8, 2007]), are smaller than those defined in most fine network models, so they can not be used to accommodate occupants as they do in STEPS. Nevertheless, the grid network in SIMULEX inherits the distance map function. SIMULEX executes a similar algorithm (see Section 2.4.1.2) in STEPS to recursively calculate the distance from any block in the grid network to its nearest exit. The distances are then associated with the corresponding blocks to form a distance map. Apart from the default distance map that takes all exits into consideration, SIMULEX allows additional distance maps to be created with all sorts of combinations of exits to reflect the variation in occupant familiarity with the exits. Similar to the escape behaviour modelled in

STEPS, occupants in SIMULEX follow the distance maps to reach an exit during the simulation. The model firstly identifies the closest block to the occupant's current location and then examines the distance information of this block's surrounding 21×21 neighbouring blocks to find the optimal travel direction to the exit for the occupant. The angle generated by this approach can be accurate to ±2.6° [Thompson & Marchant, 1995a].

In SIMULEX the grid network is not utilised to maintain the minimum separation between occupants, so the occupant body shape has to be explicitly represented to simulate close contact between any two occupants. The developers did not adopt the usual ellipse representation of body shape suggested by Fruin [1971] and Predtechenskii and Millinskii [1978] due to its complexity in mathematics; instead, they modelled the occupant body using a simple approximation to the human body. Their representation of the human body, as shown in Figure 2.17a from a plan view, is formed of one big circle (main body) and two small circles (shoulders). The size of this representation is determined by the radii (R_t and R_s) of the circles and the distance (S) between the centres of the circles.



(a) A three circle representation of body shape (b) Inter-person distance

Figure 2.17: Representation of human body and inter-person distance in SIMULEX. [Thompson & Marchant, 1995a]

This representation simplified the procedure of assessing body contact. To predict a potential collision between two occupants, the model calculates 9 inter-person distances between the 3 centres of the 2 bodies (see Figure 2.17b). If any of the distances is equal to the sum of the radii of the two corresponding circles, the two occupants are in immediate contact.

The inter-person distance is also used to simulate the change of occupant travel speed when there is an obstruction ahead in the moving occupant's travel direction. It was found [Thompson 1994] through the analysis of the video footage recorded on-site that people start to slow down when the inter-person distance is less than a certain threshold value; and the walking speed drops to zero when there is no space between the approaching individual and the other individual who obstructs the movement. In SIMULEX, the forward path of every moving occupant is scanned to detect any potential obstruction. The inter-distance to the closet obstructing person is assessed to reduce the walking speed of the moving occupant according to the inter-person distance/speed formula derived from the observation data.

If the occupant approaching from behind is already obstructed by other slow moving or stationary occupants, they may consider overtaking the obstructing person to take advantage in the evacuation. In such a case, SIMULEX estimates two new potential travel directions towards both sides of the obstructing person for overtaking [Thompson & Marchant, 1995a]. The one with minimum deviation from the original travel direction will be selected if it allows the occupant to quickly pass by the obstructing person. See Figure 2.18 for instance. An occupant approaching an obstructing occupant from behind assesses two potential angles of overtaking, θ_1 and θ_2. This occupant will try to overtake from the right since θ_1 is smaller than θ_2. Overtaking normally happens in less dense occupant flows. Once the occupant density exceeds a certain value (2 persons/m^2) the option of overtaking will not be considered due to the lack of enough free space [Thompson & Marchant, 1995a].

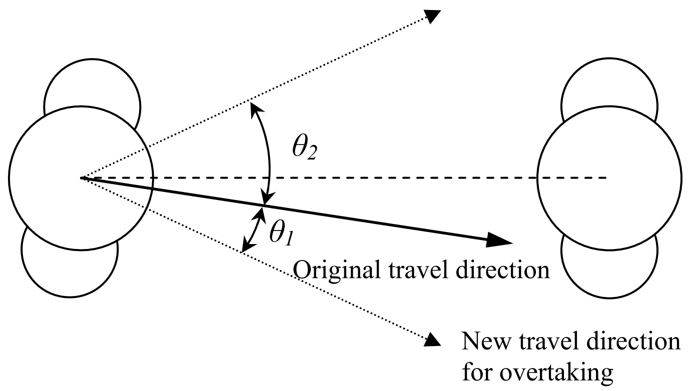


Figure 2.18: An occupant assesses two potential angles for overtaking from behind.

Another adjustment of travel direction takes place when the occupant is travelling by a solid object, e.g. a wall. If SIMULEX detects a potential contact between the occupant and the object, it will make a slight adjustment of the occupant's travel direction to keep the occupant a small distance (50 mm) away from the surface of the object.

SIMULEX, with the continuous approach, can simulate the occupant movement in fine detail. Not only does SIMULEX represent occupant position on a continuous space, but it simulates occupant steering and adjusting speeds in a relatively naturalistic and smooth manner. In addition, this method influences the way in which SIMULEX simulates occupant retrieving information and how they interact with the other occupants and the environment. More specifically, the model includes the algorithm to detect potential obstructing objects in the travel direction and simulate occupant's response by adjusting their travel speed and direction. Although the aim of this algorithm is to reproduce the observed human movement in simulation, it provides an analogue to the process in a real situation in which people use visual perception to collect information, interpret the environment and then make a decision. This perception ability is more explicitly represented in another continuous model, MASSEgress.

FDS+Evac

FDS+Evac [Korhonen *et al.*, 2005, 2007; Korhonen & Hostikka, 2008] is a combination of the Fire Dynamics Simulator (FDS) [McGrattan *et al.*, 2008a, 2008b] developed at the National Institute of Standard and Technology (NIST) and the evacuation model developed at VTT Technical Research Centre of Finland. FDS+Evac is similar to SIMULEX in several aspects such as the method of modelling the virtual built environment, the occupant's body shape and the use of map systems. However, the developers implemented a completely different occupant movement model based on the social force model [Helbing, 1991; Helbing & Molnár, 1995; Helbing *et al.*, 2002]. The model also takes the results produced from the fire simulation program and simulates the interaction between occupants and fire products. Therefore, the following analysis is focused on these aspects of FDS+Evac that are different to SIMULEX.

The implementation of the occupant movement model in FDS+Evac was originally inspired by the social force model developed by Helbing *et al.* [1991, 1995, 2002]. This model treats occupant movement as an analogue of Newton's Second Law of motion which describes the relationship between the motion of an object and the forces acting on the object. The actual movement of an occupant in FDS+Evac is determined by Equation 2.7 and Equation 2.8 [Korhonen & Hostikka, 2008], which govern the translational degrees of freedom and the rotational degrees of freedom respectively in the 2D geometry.

$$m_i \frac{d^2 x_i(t)}{dt^2} = f_i(t) + \xi_i(t)$$ **(Equation 2.7)**

$$I_i^z \frac{d^2 \varphi_i(t)}{dt^2} = M_i^z(t) + \eta_i^z(t)$$ **(Equation 2.8)**

The meanings of the variables in the two equations are listed in Table 2.3.

Table 2.3: Meaning of variables in Equation 2.7 and Equation 2.8.

Variable	Description
m_i	The mass of occupant *i*.
$x_i(t)$	The position of occupant *i* at time *t*.
$f_i(t)$	The combination of the forces exerted on the occupant.
$\xi_i(t)$	A small random fluctuation force.
I_i^z	The mass moment of inertia of occupant *i* about the vertical axis (*z*-axis).
$\varphi_i(t)$	The angle of occupant *i* at time *t*.
$M_i^z(t)$	The total torque exerted on the occupant.
$\eta_i^z(t)$	A small random fluctuation torque.

The forces, $f_i(t)$, exerted on the occupant come from three main sources. The first is the internal motivation which determines the acceleration of the occupant towards their desired velocity of motion. The effect of this acceleration is to let the occupant maintain their maximum travel speed towards this target. The second is the impulse to keep a certain distance from other occupants and obstacles. When other occupants are present in close proximity, the occupant has to slow down or change their travel direction to avoid direct contact and collision. The occupant is effectively held back by a virtual social force. All of the forces described acting together on the occupant to determine the occupant travel speed and direction. Similarly, the total torque $M_i^z(t)$ exerted on the occupant includes the torques of contact, social and motive forces. And it determines the rotational speed and direction of the occupant body.

FDS+Evac [Korhonen & Hostikka, 2008] adopts a similar but slightly different approach compared with SIMULEX in guiding occupants towards exits. FDS+Evac creates a nodal mesh that covers the entire geometry. Each square node (measured 0.25×0.25 m by default) bears a vector to indicate the preferred travel direction for anyone who is located at or in close proximity to this node. The vector is not obtained by distance calculation as the algorithm in SIMULEX does, but by solving it as an analogue of the potential flow of a 2-dimentional incompressible fluid with given boundary conditions. The direction vector field generated in this way is different from that in SIMULEX. Theoretically the vector field will disperse the crowd evenly in the passage, while the route followed by occupants may not be the shortest one.

The combination of the FDS program with the evacuation program enable the influence of fire related products upon the evacuating occupants to be examined [Korhonen & Hostikka, 2008]. The influence of fire products is addressed from four aspects in the model:

- the impact of smoke on walking speed,
- fire detection,
- the toxic effects of gases,
- and the influence of smoke and gases on occupant exit selection.

The modelling of the impact of smoke on walking speed is based on Frantzich and Nilsson's experimental study [2004].

The presence of smoke in buildings would normally be treated as a cue of threatening conditions that triggers an immediate evacuation. In FDS+Evac the smoke density can be defined as a condition to override the occupant response time. This is to simulate the process in which the occupants detect the fire and start to evacuate by perceiving smoke that exceeds a certain threshold value.

The toxic effects of gases are modelled by introducing Purser's Fractional Effective Dose (FED) [Purser, 1995] model into FDS+Evac. The model calculates for every occupant an FED value which represents the accumulated effect of exposure to narcotic gases, CO, CO_2 as well as the accumulated effect of hypoxia due to low O_2. An occupant will become incapacitated once the FED value exceeds a threshold value.

Finally, FDS+Evac utilises the FED calculation and reduced visibility due to smoke to influence occupant exit selection. The FED value that an occupant is going to suffer by using a particular exit is estimated. This exit is considered as unusable if the value is larger than unity. In addition, the smoke density is used to estimate the visibility distance of an exit and, the exit is considered as unusable if the visibility is smaller than 0.5*distance to the exit. Even if an exit is usable, the presence of fire related products around this exit is considered as disturbing conditions that reduce the likelihood of an occupant choosing that exit during an evacuation.

MASSEgress

MASSEgress [Pan, 2006] (Multi-Agent Simulation System for Egress analysis) is a recent evacuation model developed by Xiaoshan Pan at the Stanford University. MASSEgress models an occupant as an intelligent agent equipped with a perception system (sensors), a decision system (brain) and a motion control system (actuator). Unlikely the agents in STEPS, EGRESS, SIMULEX and FDS+Evac discussed previously, which passively follow pre-calculated distance/potential map to find their way to a desired destination, the agents in MASSEgress are more active in acquiring information and sensitive to the situation perceived. Through the perception of the other agents' actions and adaptive decision-making, the agents can demonstrate complex social behaviours, such as competitive, queuing, herding, altruistic and leader-following.

The basis of MASSEgress in modelling an occupant is that an intelligent agent can sense the environment through visual perception, aural perception, oral communications and sense of touch that people use in real life; the information collected though perception systems feeds to the decision system and then determines their movement and behaviour. Pan [2006] selectively implemented a visual perception system for its major role in acquiring wayfinding information for navigation in an evacuation.

The visual perception is modelled in MASSEgress through the concept of view volume. A view volume is a cone area extended in the forward direction in which the occupant is facing. It is described by a visual perception range (V_r) and a view angle (θ). Any object falling in this cone is visible to the occupant unless it is blocked by another obstacle. In the example of the view volume of occupant P_0 shown in Figure 2.19, both occupant P_1 and exit E are visible to P_0, while assembly point A (out of visual perception range) and occupant P_2 (blocked by a wall) are not.

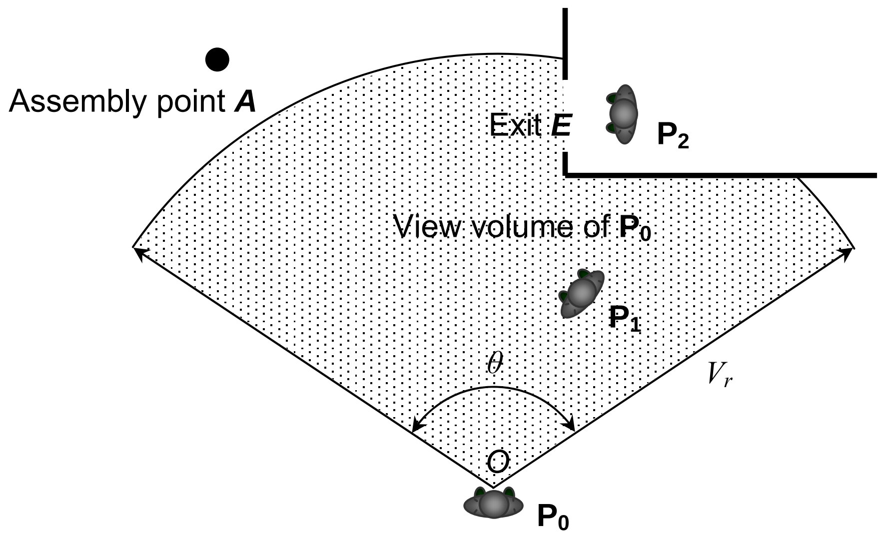


Figure 2.19: The view volume concept in MASSEgress [Pan, 2006].

It would significantly impair the simulation speed to implement a visual perception system that frequently scans the entire view volumes of all occupants for visible objects. In order to solve the problem, Pan adopts a hybrid approach for detecting different types of objects in the actual implementation of the visual perception system in MASSEgress.

Firstly, for objects that are relatively small in quantity in buildings, e.g. exits, signs and assembly points, a point test algorithm is used to determine whether they are visible to the occupant (within the view volume). This algorithm influences the occupant global escape behaviour since these objects provide crucial information for navigation and wayfinding. For instance, the definition of visual perception range determines how far the occupant is able to 'see' and influence their behaviour of searching for an exit.

Secondly, a pre-computed grid network is utilised to detect potential collision between occupants. This approach is similar to what has been employed in the fine network models. In MASSEgress every occupant inside the building is always registered with a node close to their current position. Before the occupant tries to move to a new location, they check those neighbouring nodes around. A conflict is predicted if another occupant is currently located at or plans to move towards the point which they intend to move to. The occupant then adjusts their intended movement to avoid such a collision. Once the occupant is moved, they will be unregistered with the previous node and registered with another node close to their new position. It should be pointed out that the occupant is not necessarily located at the centre of a node since the MASSEgress model traces the occupant location in a continuous space using a coordinate system.

Finally, a simple ray tracing algorithm is implemented to detect other stationary objects, e.g. walls and obstacles, which require less attentiveness to the occupants. This algorithm is mostly used to perceive structure information about the building. It helps the occupant detect and avoid a collision with stationary obstacles and boundaries in the geometry. At each time step, three rays with the length of V_r are cast along the left and right boundary as well as in the middle of the occupant's view volume. The occupant will perceive the presence of an obstacle if any of the rays intersects with the boundary of the obstacle. Consequently, the occupant will steer away to avoid a collision with the obstacle. Figure 2.20 shows an occupant using this approach solely to navigate through an L-interaction.

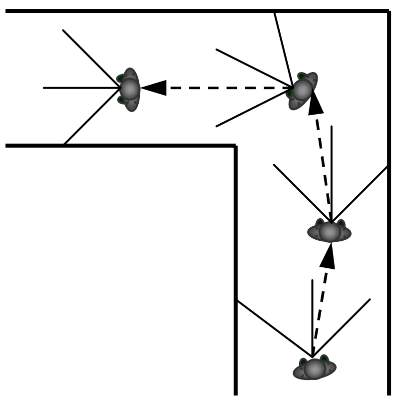


Figure 2.20: An occupant navigates through an L-intersection in MASSEgress [Pan, 2006].

The occupants can form an understanding of the environment within the perceivable range with the information perceived though the visual sensors. It includes the presence and locations of the other occupants, obstacles, exit signs, exits and assembly points. In addition, the occupants can recognise the specific types of the objects with added attributes to the objects. For instance, they can differentiate a leader from a group of occupants and may consider following the leader. The information enables the occupants to assess the situation and make a personalised decision during a simulation.

The modelling of occupant behaviour in MASSEgress is processed in two steps. Pan firstly analysed five typical occupant behaviours observed in evacuation to identify the crucial parameters and processes involved, and consequently, incorporated the sensory data into modelling these behaviours. The specific types of behaviour include competitive behaviour, altruistic behaviour, queuing behaviour, herding behaviour and leader-following behaviour.

At the second step, Pan designed and implemented decision trees to simulate the occupant decision-making process under different stress levels. A decision tree is composed of decision-making rules organised in a tree structure. The behaviours identified in the first step become the leaf nodes of the decision trees; when a corresponding condition is met, one of the behaviour options will be selected as a behavioural decision and executed by the motion control system.

Pan [2006] has made an effort to introduce a number of new concepts to model intelligent agents, aiming to construct an analogue of occupants perceiving information, decision-making and acting in a realistic situation. However, the development of the MASSEgress model was primarily based on a theoretical analysis of occupant evacuation behaviour. Since the novel concepts involved in the model development were not empirically tested and the basis of most model components lacks validation from empirical data, Pan [2006] had to validate the model as a whole against the other validated evacuation models (SIMULEX and buildingEXODUS).

2.4.2 Discussion

2.4.2.1 Evolvement of Evacuation Models and the Approach Representing Building Space

Computer models for evacuation simulation have evolved over four decades since the 1970s [Francis & Saunders, 1979; Stahl, 1982]. The evolvement of evacuation models reflects the progress in the development of computational power, modelling techniques and more importantly, the research into occupant movement and behaviour in evacuations. In order to gain an understanding of the modelling techniques used and the capabilities of evacuation models, seven representative computer models are selected from a range of available models and discussed in this chapter.

The early attempt [Francis & Saunders, 1979; Kisko *et al.*, 1985, 1986, 1998] of modelling building evacuation adopted a simple approach to represent building space and mostly focused on the physical aspect of evacuation process, while no or less behavioural features were represented. EVACNET for instance, simulates the building in question as a coarse network consisting of nodes (representing building components) and links (representing node connectivity) and simulates evacuation as solving a network optimisation problem. Since each node is a simple representation of an entire (or part of) building component, this approach can not determine individual occupant location within the corresponding building component.

Therefore, it is difficult to explicitly represent any location related behaviour, such as occupant-occupant interaction [Gwynne *et al.*, 1999b].

The requirement for a better understanding of occupant movement and behaviour during an evacuation led to efforts to develop new modelling approaches and simulate intelligent agents capable of interacting with other individuals and the environment. Enabled by the rapid development of computer modelling technology, a number of major models such as STEPS, EGRESS, buildingEXODUS, were developed in the 1980s and 1990s. A common feature of these models is a new representation of building space based on a fine network approach, which was somewhat inspired by the analogy between the way in which particles/incompressible fluid move to reduce the potential and the way in which evacuees move to reduce the distance to the nearest exits during an evacuation. The fine network approach maps building space with a fine mesh of nodes, so that building occupants can be explicitly represented as individuals, and their location and transition can be traced in detail in simulation.

The fine network is not only used to map the physical building spaces, but also as a source of information for modelling various occupant behaviours. The most common forms of information represented in the nodal network include wayfinding information and environmental conditions. The wayfinding information is frequently represented in the form of distance/potential map systems. The map calculated prior to simulation can help identify the direction from any node inside the building to a neighbouring node as one step of the route leading to a nearest exit or a particular destination (e.g. a familiar exit or an assembly point). Apart from the map systems, wayfinding clues such as signage systems and environmental conditions such as the presence of fire hazards can be simulated too [Filippidis *et al.*, 2003, 2006; Gwynne *et al.*, 2001].

In Kuligowski's review [2005, 2008] of 30 evacuation models, the fine network models account for 40% of the models reviewed. Despite the wide application of the fine network approach, the accuracy of representing occupant local position and travel direction is constrained to some extent.

Firstly, the fine network approach maps building space using nodes of uniform size and shape. Every individual occupies a node at any time, so occupant position is bundled with the node. This method will generate a small deviation compared with the realistic situation in which people can literally locate at any point of free space inside the building. This may not have a significant impact on the simulation when examining a low density evacuating population in a relatively open space. However, when simulating an evacuation involving a high density crowd and especially in a confined space, physical contact and conflict between occupants in close proximity may become no longer negligible. Whereas the fine network approach is unable to directly simulate the contact and conflict, model developers have to resort to an indirect way to represent the effects of contact and conflict. For instance, an arbitrary small delay is introduced in buildingEXODUS as the penalty for resolving a conflict between two occupants who attempt to move to the same node at a time [Galea *et al.*, 2004].

Secondly, the occupants in a fine network model can only travel in the direction represented by the link connecting two adjacent nodes. This will generate another small deviation compared with the realistic situation in which people can literally face and travel in any viable direction. Figure 2.21 shows an example of an occupant at the top right corner of a rectangular room heading towards an exit at the bottom left corner. In a realistic situation, the occupant would normally walk straight towards the exit (depicted as a solid line) to minimise the travel time if they can see the direction of the exit and there is no obstacle in between. A fine network model has to implement sophisticated movement along the straight path, while it results in the occupant marching in a zigzag manner with frequent change of travel direction. This deviation may also reduce the simulation accuracy when travel direction becomes a factor that influences the interaction between occupants and other objects such as signage [Filippidis *et al.*, 2003, 2006].

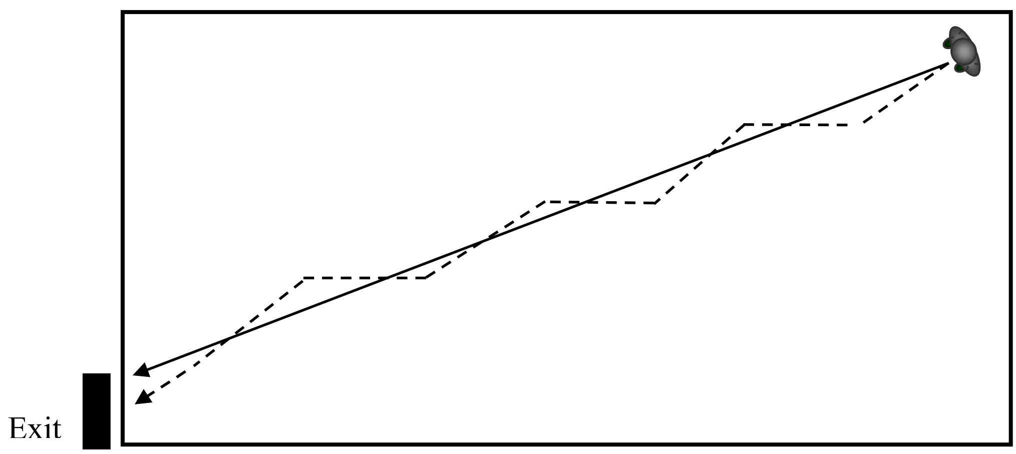


Figure 2.21: The paths adopted by occupant in two situations: in reality and in simulation.

Finally, the potential and distance map systems are frequently used in the fine network models (similar map system is also used in some coarse network and hybrid fine network/continues models) to distribute information in the network for occupants to navigate and find their desired destinations during simulation. The underlying assumption of using the potential map system is that occupants are aware of the location of all available exits; therefore, they are always able to pick up the nearest one and follow the shortest route leading to this exit. Similarly, the use of the distance map assumes that occupants know the location of certain target and always follow the shortest route to reach the desired destination. In both cases, this method simulates an ideal situation which is prone to over-deterministic occupant exit route/door selection and over-optimal individual performance. In reality people seldom act in this optimal and mechanical manner. Instead, people's route choice is subject to a variety of influencing factors, including their degree of familiarity with the building structure [Sime, 1985; Benthorn & Frantzich, 1999; Shields & Boyce, 2000], the environmental conditions [Gwynne *et al.*, 2001], the presence of wayfinding clues [Filippidis *et al.*, 2003, 2006] and the interaction with other occupants etc. People would respond to the situation they are faced with by making an adaptive decision according to the available information. As a result, the actual route choice demonstrated is often non-optimal and adaptive. To simulate these behaviours and enhance models using the map systems, model developers have tried to incorporate the findings from various experimental studies of human behaviour into their models. The efforts usually include adjustment made to the default map system and added rules that activate changes in occupant movement and behaviour under certain conditions. The improvement would not fundamentally change the fine network approach as its principle of simulating occupant movement is based on an analogy to incompressible fluid or particles following the gravity, while people can actively interact with the environment and follow their internal impulse and judgement of the situation to progress.

Knowing the limitations of the fine network approach, model developers tend to find alternative approaches that allow the simulated occupant to move and steer more freely in the simulated environment. This effort has led to the development of the continuous approach, which provides not only higher accuracy in representing occupant local position and travel direction, but also additional flexibility in modelling occupant movement and wayfinding behaviour as compared with the fine network approach.

Unlike the fine network models, of which the modelling of occupant movement relies on the virtual nodal network, the developers of the continuous models are at liberty to implement a suitable method of simulating occupant movement. For instance, the continuous models

SIMULEX, FDS+Evac and MASSEgress previously described implement different occupant movement models subject to the developers' intention.

As an early continuous model, the development of SIMULEX was apparently influenced by the fine network approach; therefore, the developers of SIMULEX adopted a similar approach to simulate occupant movement. The model creates the distance map system based on a nodal division of the building space to guide the occupants in simulation, but as smaller nodes are defined it achieves a higher accuracy in representing occupant travel direction than the fine network models [Thompson & Marchant, 1995a]. The other improvement in SIMULEX is that occupants can detect obstructions within a certain range in their travel direction and respond by either reducing travel speed or changing travel direction.

The developers of FDS+Evac implemented the social force model to simulate occupant movement and interaction with other people. The model defines a grid of nodes to cover the building space. Each node bears a vector pointing to an optimal travel direction to an exit. This direction, however, is not used as the actual travel direction for an occupant at that location. Instead, the vector is a parameter in the social force model to represent the occupant's desired travel direction. The actual travel direction is estimated by taking into account both the occupant's desired travel direction and the presence of other occupants and obstacles as a combined effect of social forces exerted on the occupant.

In MASSEgress, the occupant movement is controlled by individual perception system, decision system and motion control system. The decision system takes an input from the perception system to form an understanding of the immediate environment. The system then goes through a decision tree to decide a proper action to take and pass it to the motion control system to execute. Although the developer includes a grid network in the model, it is only used to detect potential collision between occupants.

These three models simulate different levels of agent's ability to 'communicate' with the environment compared with the 'traditional' fine network. Agents in SIMULEX can scan their travel direction to detect any obstructing objects and adjust their travel speed or direction to avoid a collision. FDS+Evac utilises the information about the presence of other agents and obstacles within an effective range to calculate an agent's travel speed and direction; it achieves the same effect as a visual perception system. In MASSEgress, agents utilise the information collected by an explicitly defined perception system and follow the decision made by their decision system. While SIMULEX and FDS+Evac still rely on the map system to guide agents to an exit, they demonstrate the tendency to simulate people's perception system for modelling movement; MASSEgress makes a further step to simulate occupants mainly making use of their perception system in movement as well as to find a goal and navigate in the building.

In the mean time these sophisticated occupant movement models inevitably introduced a variety of parameters into the simulation. How to supply proper values to these parameters and validate the models becomes a challenge faced by the model developers due to the difficulty involved in obtaining necessary data and the uncertainty in the influence of these parameters on the simulation results.

These seven representative models described show the continuous efforts in the development of various evacuation models. These efforts have pushed the model development from modelling an evacuating population as unified agent flows towards more complicated behaviour-oriented occupant movement model and, the extra flexibility brought by the fine network and continuous approaches enables more complex and sophisticated behaviour features to be modelled and implemented.

2.4.2.2 Modelling the Interaction with Signage Systems

The simulation of occupants in evacuation includes two major tasks. One is to simulate the way in which occupants find an appropriate route leading to a desired destination or an exit, i.e. the wayfinding process. It involves occupants continuously picking up information from the environment, interpreting and making decisions while moving towards the destination [Passini, 1992]. The other task is to simulate the physical movement of occupants along the intended route to reach the destination. It involves occupants travelling at certain speeds and in certain directions whilst interacting with the other movable and stationary objects in close vicinity.

In spite of the substantial efforts devoted towards the modelling approach and the myriad of models, there is a relative lack of emphasis on the methods for addressing how occupants select their exit route/exit door and may adapt their selection according to the information available to them during an evacuation (see the description of the representative models in Section 2.4.1). The majority of evacuation models either rely on assumptions, e.g. assuming occupants know the locations of all exits so that they can always follow the shortest route option e.g. the distance/potential map systems, or let the model user explicitly prescribe the wayfinding strategy employed, e.g. manually assigning target destinations and exits to be used by occupants. When occupants are heading towards their destination, they are less likely to change the course due to a lack of or inadequate ability of perceiving information. This is apparently a simplification of the realistic situation, as it only represents an ideal or a presumptive situation; whilst it omits occupant's activities to perceive external information from the environment and use the information to make a selection of exit route/exit door during an evacuation.

The lack of consideration of how occupants perceive and use information in an emergency is also reflected in related safety legislation and standards, as there is no information regarding how occupants make use of the safety products and follow the intended procedure and guidance to achieve a safe escape (see Section 2.2). Thus, there are three successive questions left unanswered.

1. What is the effect on occupant safety if a safety design in a building does not fully conform to the current provisions, and how to identify the potential issues of the design?

2. If the safety design fully conforms to the current provisions, will occupants understand and react as expected, i.e. what is the likelihood of occupants correctly comprehending and utilising the safety design during an emergency?

3. If the safety design which fully conforms to the current provisions is not efficient as expected, how to improve it?

To address the above three questions, some model developers realised the importance of correctly representing occupant wayfinding behaviour including their interaction with safety signage systems. A few models such as PEDROUTE, buildingEXODUS and MASSEgress tried to include a representation of signage systems and the corresponding influence on evacuation. In summary of the three models, the features of the signage sub models implemented are listed in Table 2.4.

Table 2.4: The features of the signage sub-models implemented.

List of Model Features	PEDROUTE (v5)	buildingEXODUS (v4.0)	MASSEgress [Pan, 2006]
Space Representation	Coarse network	Fine network	Continuous
Visibility of Sign	Not addressed	Addressed through the concept of visual catchment area of signs	Addressed through the concept of view volume of agent
Factors considered in determining visibility of sign	No	Maximum viewing distance (based on relevant definition in standards); Physical factors including average height of occupant, signage mounting height and height of any obstacle between occupant and sign	View angle and perception range, but no theoretical basis is given; Presence of obstacle
Representation of the Influence of fire hazards (smoke) on Visibility of Sign	No	No	No
The way of 'seeing' sign	Signs catch agents	Signs catch agents	Agents catch signs
The process of Perception and Psychological Influencing Factors Represented	A single global probability, SPRO	Relative orientation between occupant and sign; Multiple probabilities addressing both attentiveness and compliance, but all of them adopt arbitrary values	No.
Type of interaction behaviour	User defined	Emergent behaviour	Emergent behaviour

It can be seen from PEDROUTE's implementation [PEDROUTE V5 Manual] that the simulated interaction between occupants and signage is a deterministic process (user defined) rather than an emergent behaviour as it should be. The introduction of SPRO was an attempt to catch the uncertainty nature in the interaction. However, as it is a global variable, all signs have the same compliance rate regardless of the type, visibility range and position of the signs. As a result, the signage sub model in PEDROUTE can only be used, subject to the model user's intention, to roughly assess the impact of signs upon occupants.

The implementation of signage model within buildingEXODUS [Filippidis *et al.*, 2001, 2003, 2006] was based on a well-established framework. This framework takes account of both the physical factors influencing signage visibility and the psychological factors influencing the potential interactions between occupants and signs. Yet the model has several areas which require further research and development. Firstly, the method of assessing the visible range of signs through the single maximum viewing distance has been shown to be implicit as discussed in Section 2.2.3.1. Secondly, it lacks consideration of the visibility of signs in extreme conditions, e.g. a fire scenario with smoke. Thirdly, as normally an agent can only face in a few fixed directions in the network of nodes, see Figure 2.10 for instance, the influence of relative orientation between an agent and a sign can only be assessed in a discrete manner. And finally, there is a need to quantitatively address the psychological aspect of the interaction.

A unique feature of MASSEgress is that it attempted to simulate people's visual perception system [Pan, 2006]. The simulated agents can perceive objects, including exit signs, within a visible range that is outlined by a perception range and a view angle (see Figure 2.19). The directional information conveyed by exit signs is then passed to the agent's decision system for wayfinding to a final exit or a place of safety. The merit of this method is that it simulates the interaction with signage in a natural way, while the methods used in PEDROUTE and buildingEXODUS reflect a compromise between computer modelling and the interaction process. However, the MASSEgress signage model lacks consideration of two essential aspects of the interaction. Firstly, no theoretical basis is given for defining the visible range in terms of the perception range and view angle. The visible range does not differentiate objects of different size, type and properties. For instance, a sign is visible within the same perception range as any other larger objects such as occupants and walls. Secondly, it takes no account of psychological factors that may influence the likelihood of occupants perceiving, interpreting and utilising the signs.

There are some other models which claim to include a representation of signage systems, including ALLSAFE, BGRAF, E-SCAPE, EvacSim, Legion, MOBEDIC(EGRESS) and SGEM. However, less information is available regarding how their signage models are designed and what are the theoretical bases [Kuligowski & Peacock, 2005; Kuligowski, 2008]. Therefore, the functions of signage in these models are briefly summarised here in Table 2.5.

Table 2.5: The summary of the signage function in models.

Models	Function of Signage in the Model	Influence
ALLSAFE	Signage is defined as one of the safety measures, which effectively reduce evacuation time.	Evacuation time
BGRAF	Signage is one of the factors that affect the orientation and way finding behaviour of building occupants.	Preference level
E-SCAPE	Signage, along with distance to exit and frequency of use of exit, is a factor that influences occupant's route choice.	Route choice
EvacSim	Exit sign is used to designate certain exit. It is one of the factors that influence occupant's exit choice.	Exit choice
Legion	Unclear	Route choice
MOBEDIC(EGRESS)	Sign system is modelled as one type of the information points. It gives the marked route a higher priority than others.	Route choice
SGEM	Sign is modelled as one of the factors that influence occupant's local route choice within a node (representing a room, a corridor or a part of a hall).	Local route choice

Apart from these evacuation models, studies on signage systems are conducted through agent-based simulation (ABS) of spatial cognition and wayfinding in both emergency and circulation conditions. Hajibabai *et al.* [2007] simulated people's spatial cognition with due attention to signage and fire propagation in an emergency evacuation to evaluate the total evacuation times for different designs of signage systems. Raubal [2001] developed a perceptual wayfinding model to study the need of wayfinding information at decision points. Both studies bypass the visibility, perception and interpretation aspects (see Section 2.1.2) of the interaction with signage by assuming that people will perceive and correctly interpret the information conveyed by the signs positioned in the environment.

2.5 Remarks

In this chapter, a literature review is given to expand the research questions presented in Section 1.1.3 of Chapter 1. This review analyses the interaction between occupants and signs to begin with, and it mostly focuses on four key aspects involved which address the current understanding of the interaction with signage, the viewing range of signs, the impact of smoke and the current state of representing signage in evacuation models.

As can be seen from the foregoing review, the current understanding of the interaction with signage raises concerns about the effectiveness of signage, but remains at a stage where there is a lack of quantification concerning how effective signage system is in practice.

The legislation and standards mainly focus on correct design, selection, position and maintenance of exit signs; while little has been addressed regarding how likely the signs provided will be detected, interpreted and used by occupants in an emergency evacuation. Meanwhile, the method suggested by the standards to estimate the viewing range of signs via a single maximum viewing distance is ambiguous. This is due to a lack of consideration of both the impact of smoke upon signage visibility and the influence of angular distortion. Therefore, it may not correctly represent the extent within which occupants can resolve the signs both in normal and fire conditions.

The study of the impact of smoke upon signage visibility and occupant evacuation behaviour conducted by several researchers is introduced. Whereas the data-sets collected are valuable and some have been already used, the results were not fully comprehended and utilised in evacuation modelling. Therefore, there is a potential to produce a comprehensive representation of the impact of smoke on the interaction between occupants and signs by combining the experimental results obtained from available experiments conducted.

Also in this chapter, the evolvement of evacuation models and the techniques used in model development are introduced through the review of seven representative evacuation models. The model development has evolved from initial occupant flow simulation into more behaviour-oriented simulation. The former simulates occupants and their movement in a uniform manner and is principally dominated by the simple rule of reducing their distance to a nearest exit, whereas the latter treats simulated occupants as intelligent and adaptive agents, which may interact with other agents as well as the environment. This approach usually requires the agents to perceive information and respond following certain behavioural rules. One of the sources of information is signage for wayfinding, which plays an important role in guiding occupant during an emergency evacuation. However, most evacuation models follow the same assumption as in the guidance that occupants would perceive and use signs when necessary.

In summary of this chapter, the research questions presented in Section 1.1.3 of Chapter 1 are either not fully answered or omitted previously. Therefore, the following goals are set to address these questions.

1. Identify the correct physical extent within which occupants can resolve signs under normal conditions.
2. Comprehend the data collected addressing the impact of smoke on visibility of signs as well as occupant movement and behaviour.
3. Provide quantification concerning the likelihood of occupants actually seeing and utilising the sign in a built environment in an assumed emergency scenario.
4. Based on the above three studies produce a comprehensive representation of the impact of signage on an evacuating population within an evacuation simulation tool.

Chapter 3
The buildingEXODUS Evacuation Model

In this chapter, the buildingEXODUS evacuation model is introduced with an emphasis on the features that are relevant to this research on signage as well as the proposed development. buildingEXODUS has been selected as the platform to implement and demonstrate the new development of the research. The selection of the model is not only because the model is readily accessible to the author, but also because it is a behavioural model that allows new behavioural rules to be added and tested. It should be noted that the development is not necessarily restricted to this selected model, i.e. the research can be presented and applied elsewhere.

3.1 Model Overview

The EXODUS model was initially developed to study an aviation accident during which 55 people died in an aircraft cabin fire at Manchester Airport in 1985 [Galea *et al.*, 1996a]. EXODUS has been continuously developed over the last 25 years by the Fire Safety Engineering Group at the University of Greenwich. Now it covers the simulation of occupant circulation and evacuation in aircrafts, ships and a wide range of buildings. EXODUS is a fine network model. However, it has also benefited from incorporating coarse nodes into some applications [Kinsey, 2010] and is moving towards a more sophisticated hybrid model [Chooramun, 2010]. The following description focuses on buildingEXODUS version 4.0, a fine network model, which is particularly implemented to simulate evacuation in built environments [Galea *et al.*, 2004].

buildingEXODUS is composed of five core sub-models: the OCCUPANT, BEHAVIOUR, MOVEMENT, HAZARD and TOXICITY sub-model [Galea *et al.*, 2004]. The OCCUPANT sub-model defines a collection of occupant attributes. These attributes are used to identify individuals and represent their physical, psychological status. Some of the attributes are also used to record individual's experience during the simulation. The BEHAVIOUR sub-model simulates the process of an individual making a decision according to their goals as well as their response to the current prevailing situation. The MOVEMENT sub-model fulfils an individual's intention to move and controls their movement in the building. The HAZARD sub-model introduces pre-calculated fire hazards into simulation and represents the development of fire and spread of fire hazards in the physical environment. The TOXICITY sub-model determines the impact of direct contact and continuous exposure to various hazards such as heat, radiation, toxic and narcotic products upon individuals. The influence is then transferred to the BEHAVIOUR and MOVEMENT sub-models and reflected by adaptive behaviour, reduced travel speed and agility and even incapacity. These sub-models interlace with one another and operate on a region of space (i.e. the geometry) represented by a network of connected nodes.

When simulating occupant movement in a normal situation or in an emergency evacuation, the buildingEXODUS model takes into account people-people, people-environment and people-structure interactions. These interactions are controlled by a set of heuristics or rules. When a simulated individual is faced with a specific condition, the heuristics and rules enable the individual to respond and demonstrate a corresponding behaviour or movement that simulates people's response in a realistic situation. The design of the model also allows new rules to be added and examined. Therefore, buildingEXODUS is an ideal platform for implementing and testing new behavioural features.

3.2 Node, Arc and Geometry Representation

In buildingEXODUS, a geometry sub-model [Galea *et al.*, 2004] is implemented to construct and manage a fine network representation of the simulated building. For this purpose, two basic elements, node and arc, are defined in the geometry sub-model. Each node corresponds to a fixed point within a grid representation of the building. A node can accommodate a single occupant at one time. Nodes are not only used to represent free space for occupancy, but also other terrain types (e.g. seat, boundary, landing and stair) and functions (e.g. attractor, discharge, source, direction and redirection). In addition, nodes are used as the entity to store information about environmental conditions (e.g. the presence of fire hazards) and wayfinding information (e.g. the distance/potential map and the visibility of signage). Arcs are defined to connect nodes. An arc can connect two nodes typically in three directions: horizontal, vertical and diagonal. Correspondingly, the default arc lengths are 0.5 m, 0.5 m and 0.707 m respectively (see Figure 3.1).

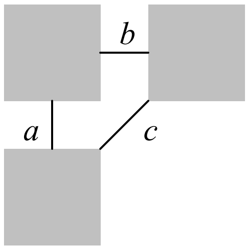


Figure 3.1: Three nodes connected by (*a*) horizontal, (*b*) vertical and (*c*) diagonal arcs.

An arc determines the connectivity (i.e. viable path) and physical distance between any two nodal locations. Hence the arc length is used in travel speed calculation and the direction of the arc is used to represent an occupant's direction of travel.

3.3 The Essence of Modelling Evacuation

The basic equation in evacuation modelling that represents the most simple egress calculation is

$$Evacuation\ \ Time = \frac{Travel\ Distance}{Travel\ Speed}. \qquad \textbf{(Equation 3.1)}$$

Travel Distance represents the total length of the route from an occupant's starting location to a destination. *Travel Speed* describes how fast the occupant moves along this route. Considering that occupants may not become aware of the abnormal situation and immediately respond to a call for evacuation, a *Response Time* is added to the equation. After an occupant has responded and started to head for an exit, they may experience congestion at any narrow passageway. After they have travelled all the way down to a target exit, there may be already a crowd of evacuees waiting to get through. Therefore, delays may occur in both circumstances due to the congestion and limited path and exit flow capacity. Consequently, a *Waiting Time* is added to the equation to account for the amount of time required to pass through any congestion and the final exit. Equation 3.1 turns into

$$Evacuation\ \ Time = Response\ Time + \frac{Travel\ Distance}{Travel\ Speed} + Waiting\ Time.$$

(Equation 3.2)

As the research on signage and the proposed development (Chapter 1) mostly concern *Travel Distance* and *Travel Speed*, the current representation of these two variables within buildingEXODUS is now described.

Travel Distance is mainly determined by the dimensions and layout of the enclosure, occupant's location and their global strategy of selecting an egress route and final exit. It is also affected by occupant local behaviour and factors that may influence occupant's selection of egress route/exit door. These factors include occupant's understanding of the building structure, the presence of wayfinding clues and the development of hazardous conditions in the building etc. *Travel Speed* is mainly determined by the occupant's initial maximum travel speed, whilst it is also influenced by the terrain being travelled over and the presence of fire hazards. buildingEXODUS includes a variety of features to simulate the influence of these factors.

3.3.1 Map System and Occupant Global Escape Behaviour

In buildingEXODUS, the occupant's global escape behaviour, i.e. wayfinding and movement towards their desired destination or an exit, is implemented upon the creation of two map systems: the potential map and the distance map [Galea *et al.*, 2004]. These two maps are calculated on the network of connected nodes (see Section 3.2).

The potential map provides distance information for every node in the geometry to its nearest exit. The use of a potential map for wayfinding is based on the assumption that occupants are aware of the building structure and the locations of all available exits, and that they prefer to use a nearest exit. The calculation of potential value for each node starts from every exit and recursively adds up the physical distance to adjacent free nodes until all nodes have been reached; i.e. modelling the need to move to the nearest exit. Every exit has a default potential value of 100. This value can be modified to make an exit more attractive (small potential) or less attractive (large potential).

The distance map is similar to the potential map concerning the algorithm used to calculate the map, but each distance map is created for a specific exit. The distance map is used under circumstances that occupants may have limited knowledge of the building structure; therefore, they are only aware of one or more exits. This corresponds to the fact that an occupant may not necessarily be aware of their nearest exit. The model simulates the variation of occupant's level of familiarity with the building by directing occupants to follow different distance maps. The use of distance map can change during a simulation to reflect the change of occupant exit knowledge (OEK) [Gwynne *et al.*, 2001] or emergency status. For instance, occupants may become aware of a previously unknown exit though communication with other occupants. Occupants may also consider using emergency exits under certain circumstances.

When looking for direction towards their desired destination or an exit, occupants check the potential or distance values of the neighbouring nodes and compare with that of the current node to decide the direction of next step movement. Through the introduction of pre-calculated map systems, the model can bypass the complexity of representing occupant's spatial awareness in simulating their global escape behaviour; besides, this approach potentially increases simulation speed.

3.3.2 Occupant Local Behaviour

Apart from the occupant global egress behaviour, *Travel Distance* is also influenced by occupant local decisions, such as the interaction with wayfinding cues, response to congestion and the presence of hazards. These decisions are represented as occupant local adaptive behaviour in buildingEXODUS.

3.3.2.1 Interaction with Signage

Once the simulated occupants begin to evacuate, they will be driven to escape as quickly as possible, often via the shortest route leading to a nearest exit. This exit is either selected from all available exits (based on the potential map) or picked up from a list of known exits (based on OEK and the distance maps). The former represents an optimal and ideal scenario, while the latter represents a conservative and more realistic scenario. Considering a realistic evacuation scenario, there is a chance that occupants may perceive and use previously unknown exits or unfamiliar emergency exits by following exit signs. This type of interaction is introduced into buildingEXODUS through a signage model [Filippidis *et al.*, 2001, 2003, 2006, 2008] to simulate the impact of exit signs on occupant's exit route/exit door selection behaviour.

The signage model consists of two parts. The first part deals with the physical visibility of signage [Filippidis *et al.*, 2001]. The second part simulates the process of occupant detecting and utilising the information conveyed by signage [Filippidis *et al.*, 2003, 2006, 2008].

There are two methods of representing the physical visibility of signage. The first method determines the visibility range of the sign from the observer's point of view. The second one, in contrast, defines the signage visibility from the sign's point of view. Given that the number of occupants in a building is likely to be much larger than the number of signs, and that the visibility ranges of moving occupants need to be frequently updated, the second method is adopted, i.e. the visibility of signage is represented from the viewpoint of sign through the concept of visual catchment area (VCA) [Filippidis *et al.,* 2001, 2003, 2006], which describes the physical extent within which it is physically possible to see the sign.

When determining the VCA of a sign, the signage model takes account of the maximum viewing distance of the sign and the reduced visibility when viewing the sign at an angle that is close to parallel to the surface of that sign. The maximum viewing distance has been frequently defined in relevant legislation and standards, while the influence of viewing a sign at large angles was only studied recently [Xie, 2007], therefore it was not explicitly addressed in the signage model of Filippidis *et al.* [2001, 2003, 2006]. The initial VCA includes all of the nodes that fall within the range from the centre of the sign to its maximum viewing distance. In order to reflect the difficulty of reading the sign at a parallel angle to the surface of the sign, the nodes located at the left and right margins are subtracted to form the final representation of the VCA (see Figure 3.2).

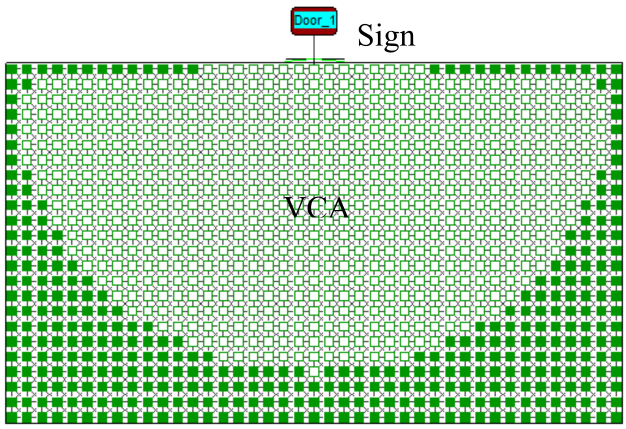


Figure 3.2: An example of Visual Catchment Area (VCA) of a sign in buildingEXODUS.

Once an occupant moves to a node within the VCA, it will be physically possible for him to receive information from the sign. The process of the occupant detecting the sign and utilising the information conveyed by the sign is simulated by the second part of the signage model in three steps. Firstly, the relative orientation between the occupant's direction of travel and the sign is examined to determine whether the occupant actually detects the sign. Secondly, if a successful detection is confirmed, it is further assessed to decide whether the occupant recognises the sign and correctly interprets the information. If all tests are successful, the exit indicated by the sign will be added into the occupant's OEK. Finally, the occupant assesses whether the new exit route offers any advantage over the routes leading to the other known exits. If it does, the occupant will redirect to it to reduce the evacuation time. The procedure of the interaction between occupants and signs is illustrated in Figure 3.3.

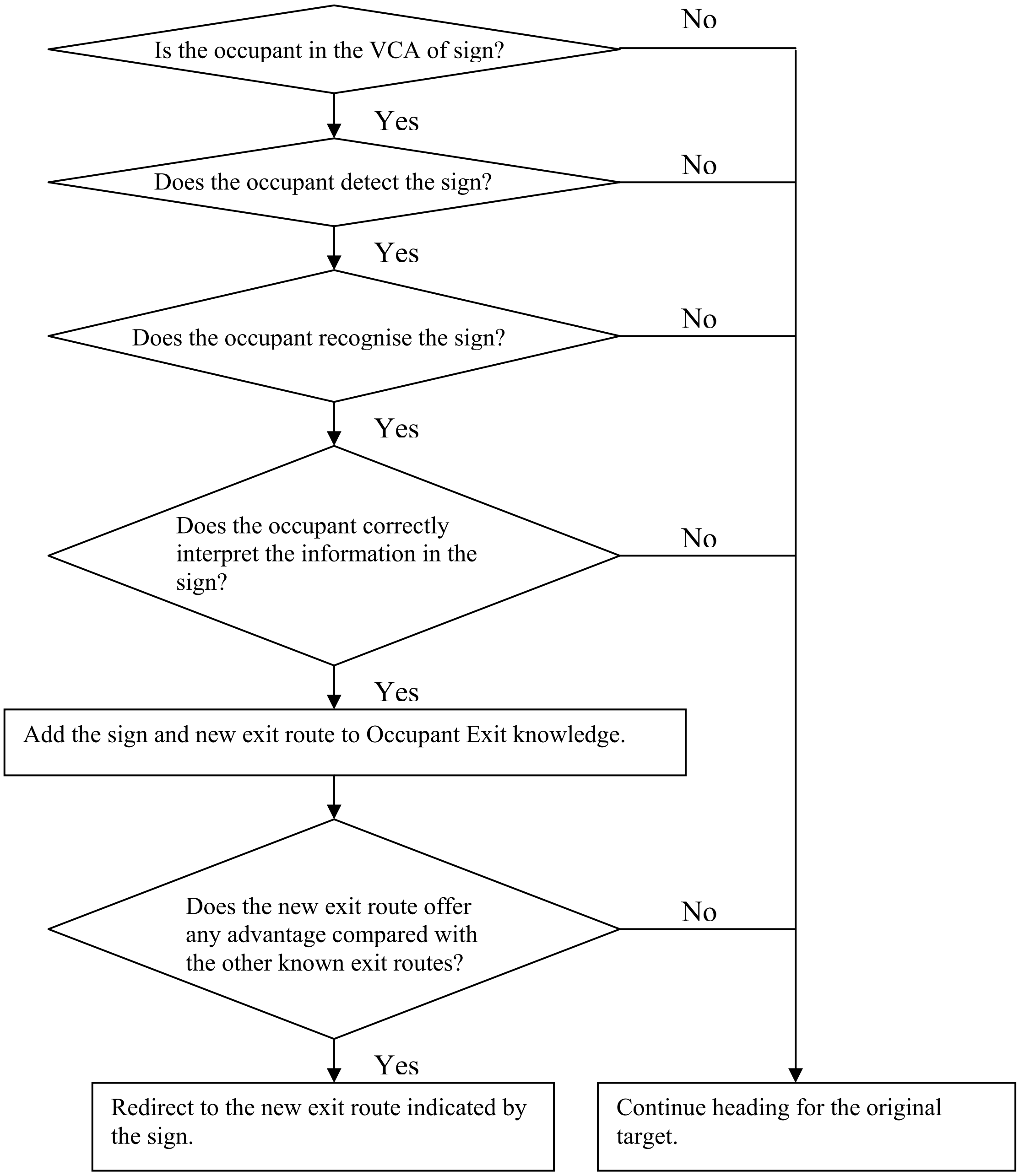


Figure 3.3: The procedure of the interaction between occupants and signs.

3.3.2.2 Interaction with Congestion

At a congested exit occupants may consider using an alterative exit to avoid being trapped in the crowd. This type of redirection behaviour due to the observed congestion is represented in buildingEXODUS. The modelling of this redirection behaviour is conducted in two steps. The first step detects the situation of congestion which initiates the interaction with congestion. The second step assesses the threshold condition which makes an occupant decide to redirect to another exit.

Occupants need to be aware of the crowd situation around an exit which they originally attempt to use before considering the possibility of using the other exit options. However, the model is faced with the same difficulty as when modelling the interaction between occupants and signs, i.e. a substantial amount of calculation is required to simulate occupant's visual perception of the environment for a large occupant population. A similar solution as in the signage model is adopted, which uses the visual catchment area of the exit to collect the information required for occupants to make a redirection decision.

To represent the VCA of an exit, an exit sign is required and positioned above the exit with which it is associated. Once an occupant heading for this exit falls into the VCA of the sign, an evaluation algorithm is executed to estimate the crowd situation around the exit and the potential benefit of redirecting to the other known or visible exits. If it requires less effort to leave the building via another exit than the current one, e.g. an alternative visible exit is less congested or the travel time to an alternative invisible exit is expected to be shorter, the occupant will consider the possibility of changing their target exit. Given the potential benefit of using an alternative exit, whether the occupant will actually redirect is subject to their location and motivation to change or maintain an objective. This motivation is modelled through a psychological attribute, Drive [Galea *et al.*, 2004], in buildingEXODUS. If the occupant is free to move and has necessary assertiveness to change an objective, they will eventually make a redirection decision.

It should be pointed out that although the occupant's intention of redirection is to reduce the evacuation time, it may not prove to be an optimal decision. For instance, if an occupant redirects to a previously invisible but also congested exit, it may increase the total evacuation time. The procedure of occupant perceiving the condition of congestion and making a redirection decision is illustrated in Figure 3.4.

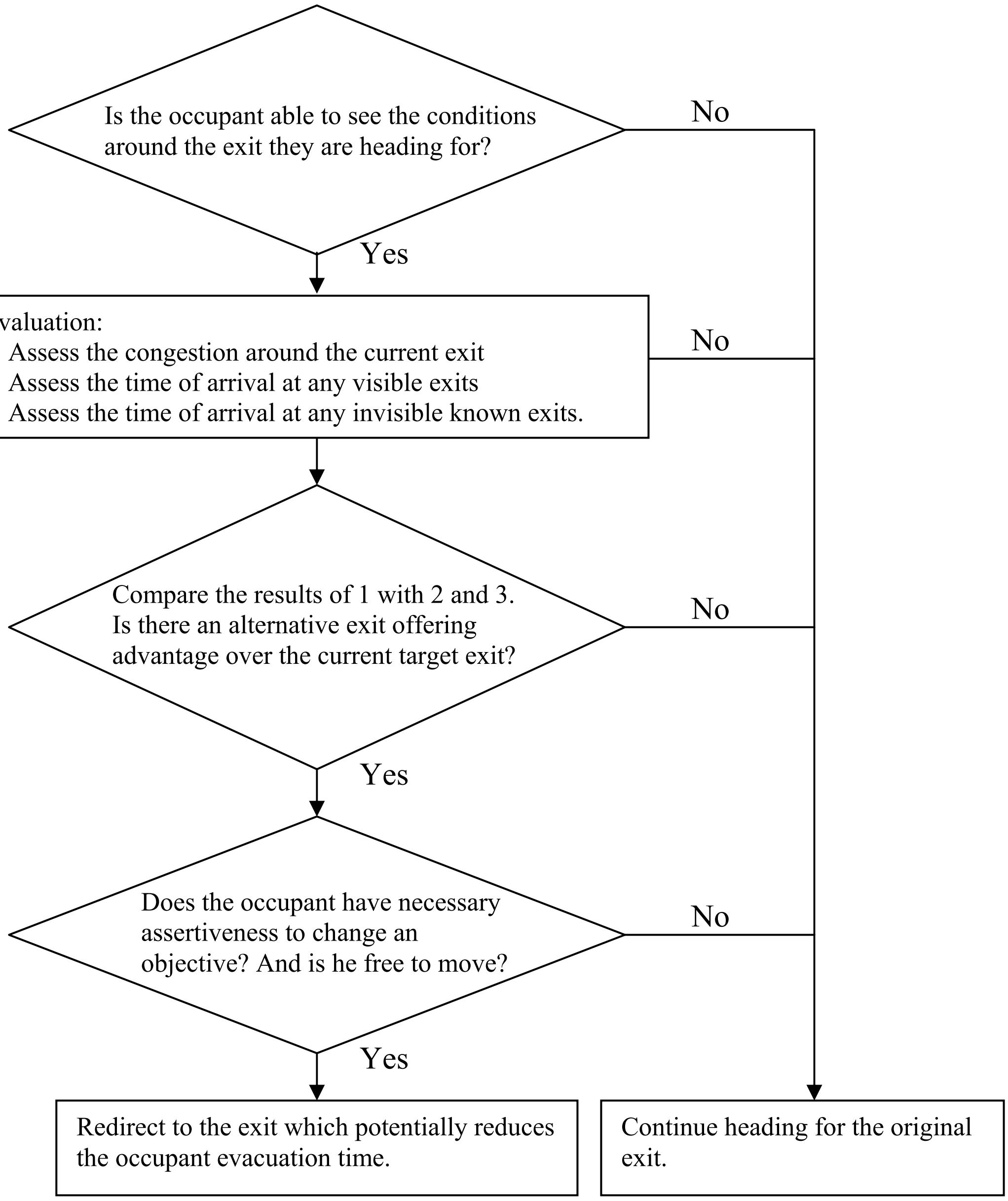


Figure 3.4: The procedure of occupant interaction with congestion.

3.3.2.3 Interaction with Fire Hazards

It is quite often that some cases of emergency evacuation are accompanied by fire and fire generated hazards. The hazards pose a threat to an occupant's well-being, and they may influence occupant evacuation behaviour too. The influence is represented in two forms in buildingEXODUS: (1) the impact of direct contact with and continuous exposure to the hazards and (2) the occupant behavioural response to the hazards [Galea *et al.*, 2004].

To simulate the interaction between occupants and fire hazards, the model incorporates a representation of the fire hazards in the physical environment. As buildingEXODUS is a dedicated evacuation model, it does not include the capability of predicting the evolvement of a fire. Thus it utilises pre-computed data generated by third-party tools to represent the development of fire and the spread of fire hazards in the building. In buildingEXODUS, the HAZARD sub-model admits fire hazard data and simulates the process of fire. The model operates on a zone division of the building. Each zone usually consists of a number of adjacent nodes. This zone division is also used by the third-party tools to produce data describing the development of fire and the distribution of hazards, so that the data can be directly imported to the corresponding zones in buildingEXODUS. During the simulation, the HAZARD sub-model reproduces the process of a fire by updating the concentrates and intensities of harmful components in the zones along with the running of the simulation clock.

The impact of various fire hazards upon occupants has been studied for decades. Model developers have attempted to introduce the results obtained into their models (such as CRISP [Fraser-Mitchell, 1999], buildingEXODUS [Galea *et al.*, 2004] and FDS+Evac [Korhonen & Hostikka, 2008]). The most commonly referred work is the Fractional Effective Dose (FED) toxicity model developed by Purser [1989, 1995, 1996, 2001, 2003, 2008]. This model is used in buildingEXODUS as the core of the TOXICITY sub-model. The impact of fire hazards upon occupant's well-being has two forms of cause: direct contact with and accumulated exposure to the hazards. The harmful effects vary from reduced movement ability to effects as serious as incapacity. These effects are calculated separately for each hazard components on the individuals, while the most serious one is selected to represent the current impact of the hazards. This impact is then reflected in the simulation through the MOVEMENT sub-model.

Apart from the impact on occupant's movement ability, the occupant behavioural response may also be influenced by perceiving the presence of fire hazards during an emergency. This is modelled in buildingEXODUS in three ways. Firstly, the presence of fire hazards, radiation in particular, would make people realise the threatening condition and then start to evacuate. During a simulation, the occupant Response Time can be overridden if the intensity of radiation exceeds certain threshold value. Secondly, the obscuration and irritant effect of smoke pose an obstacle to occupants' evacuation movement in the building. A number of experiments have been conducted in the past to examine the impact of smoke upon evacuating people's walking speed and their ability of discerning signage in smoke [Jin, 1978, 1997; Jin & Yamada, 1985, 1989; Frantzich & Nilsson, 2004; Wright *et al.*, 2001b]. Jin's work is frequently cited and Jin's Speed/Extinction coefficient formulation is used in buildingEXODUS [Galea *et al.*, 2004]. Depending on the attribute of the smoke, either Jin's irritant curve or non-irritant curve is used to specify the relationship between smoke concentration and its impact upon an occupant's walking speed. Jin also observed that people have difficulty in maintaining straight walking in smoke; instead, they walked in a zigzag manner and would prefer to seek support when navigating through dense smoke (as if in darkness). This type of behaviour is simulated in the model by introducing a distortion to an occupant's selection of node for immediate next step. As a result, not only do occupants walk more slowly in smoke than in a clear environment, but they also walk in a sub-optimal manner. Thirdly, as smoke poses a threat to the occupant's well-being, it could influence the occupant's exit route selection in an emergency. A common case is that if smoke forms a barrier that prevents the occupants from accessing their desired exit, they may walk away from the smoke barrier and look for an alternative exit route that has not yet been affected by smoke. Bryan [1977] and Wood [1972] have studied the data collected from real residential incidents. They found that the probability of occupants redirecting from a smoke barrier is somewhat related to the smoke density; a high smoke density (i.e. a low visibility through smoke) would result in a high redirection probability. Their data-sets have been incorporated into buildingEXODUS [Gwynne *et al.*, 2001]. Once an occupant detects a smoke barrier in the simulation, the likelihood of redirection is estimated according to the smoke density along their intended direction of travel.

3.4 Proposed Development and Approach

Given the initial research questions posed in Chapter 1, the current understanding of the interaction with signage and the limitations with respect to representing the interaction in existing models have been discussed in Chapter 2. In this chapter, the buildingEXODUS evacuation model as the selected platform for implementing the proposed development has been further described. The limitations of the model related to this research have been identified. The proposed developments are now described (see Figure 1.1).

- **Firstly, the representation of the signage visibility in the model needs to be improved.**

The current method of estimating signage visibility is based on the definition of the maximum viewing distance of signs, while the impact of the angular distortion and the presence of smoke upon occupants reading a sign are not addressed. The influence of the angular distortion on signage visibility will be studied through experimentation (Chapter 4). The influence of the smoke on signage visibility will be represented through an adapted Jin's model [1978, 1997, 2008] (Chapter 10). The aim is to correctly define the visibility limits of signs both in a clear environment and in smoke.

- **Secondly, the representation of the impact of smoke needs to be improved.**

buildingEXODUS uses Jin's non-irritant curve and irritant curve [Jin, 1978, 1997, 2008] to represent the influence of smoke upon occupant's travel speed. This method is limited as the curves cover a short range of smoke density. Given that additional published data-sets [Frantzich & Nilsson, 2004; Wright *et al.*, 2001b; Galea *et al.*, 2001] have become available concerning the influence of smoke, there is an opportunity to revise the representation of the impact of smoke upon occupants' evacuation performance and behaviour (Chapter 11).

- **Finally, the representation of the interaction with signage needs to be improved.**

The interaction will be studied through experimentation (Chapter 6). The aim is to identify the key factors that influence the interaction between occupants and signs and provide the quantification that is lacking in existing modelling approaches.

Chapter 4

Theoretical Analysis and Experimental Study of Signage Legibility Distances as a Function of Observation Angle

4.1 The Current Approach of Estimating Signage Visibility in Legislation and Standards

In current safety legislation and standards [ISO 3864-1:2002; BS 5499-4:2000], the visibility of signage is estimated through the maximum viewing distance. This is one of the design criteria used to determine whether a signage system is compliant. The maximum viewing distance is often defined as a linear function of the size of the critical detail (e.g. text component and graphic symbol) on the sign to be resolved, taking into account the lighting conditions and illumination on the sign (or luminance in the case of an internally illuminated sign). The area within which an occupant is able to receive information from the sign is represented as a semicircular area [Filippidis *et al*., 2001, 2003, 2006] (see Figure 4.1). The radius of this semicircle is equal to the maximum viewing distance; the centre of the semicircle is situated in the middle of the sign. This method is based on the assumption that the maximum viewing distance is independent of the angle with which the viewer is faced with the sign, i.e. it does not take account how the viewing distance is affected by viewing angle (Section 2.2.3.1, Chapter 2).

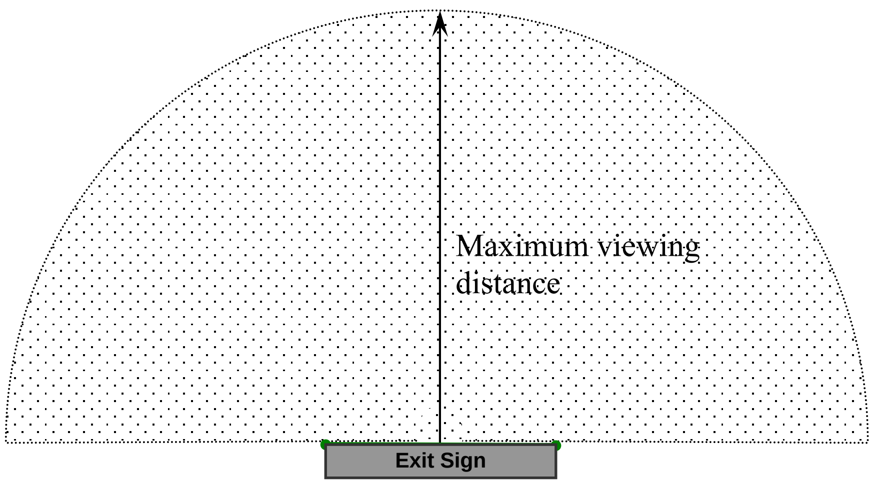


Figure 4.1: The estimated effective covering area of an exit sign.

The assumption presented in the method of estimating the visibility limits of signs contradicts the fact that it is more difficult to resolve a detail on a surface when viewing it in a large angle than in a small angle to the normal of the surface. In other words, the maximum viewing distance for reliably resolving the detail is dependent on the viewing angle. Generally, the detail should have the largest visible range when it is observed perpendicularly, i.e. from an angle of 0 degree to the normal; while the detail becomes almost illegible when the viewing angle increases to 90 degrees to the normal. Any other viewing angle between 0 and 90 degrees is expected to have a corresponding viewing distance between the maximum viewing distance and zero. If the above estimate of signage visibility limits is more accurate, the definition of signage visibility in legislation and building standards overestimates the effective area covered by signage systems. The overestimation needs to be corrected when planning and installing signage systems in buildings as well as representing signage in evacuation models. The impact of viewing angle upon the viewing distance of sign is explained theoretically in Section 4.2 and is further examined by the experimental trials described in Section 4.3.

4.2 The VCA Model and Theoretical Analysis of Signage Visibility

The concept of signage visibility has been introduced into buildingEXODUS as the first step to model the interaction between occupants and signs (see Section 3.3.2.1, Chapter 3). The representation of signage visibility was implemented based on the Visibility Catchment Area (VCA) of a sign [Filippidis *et al*., 2001, 2003, 2006]. The VCA depicts the physical extent to which the sign is visible to occupants in the simulated building. The dimensions of the VCA were initially calculated according to the definition of signage visibility in relevant legislation and standards introduced in Section 4.1. Filippidis *et al*. [2006] noticed that it is almost not possible to resolve a sign at a large angle (e.g. 90º) to the normal of the sign. However, due to the lack of reliable data linking observation angle with maximum viewing distance, a simple approach was adopted to represent this impact. That is an arbitrary small margin of 5º was subtracted from both sides of the semicircular representation of the VCA (see Figure 4.1) to form the final VCA (M_1 in Figure 4.2). In order to correctly represent the visibility limits of signage, a theoretical analysis was conducted to study the impact of viewing a sign from an angle upon the signage visibility distance. Filippidis and Blackshields *et al*. [Xie *et al*., 2005, 2007] have contributed to this work.

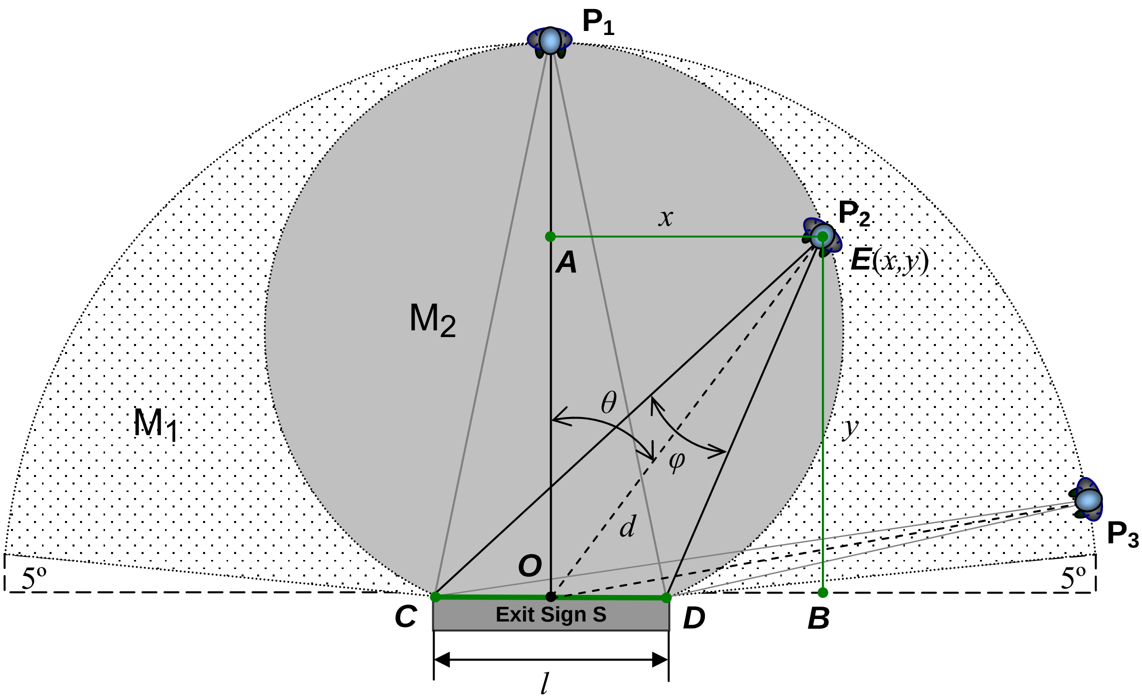


Figure 4.2: The VCAs defined by the current VCA model (M_1) and the theoretical model (M_2).

It was suggested in [Filippidis *et al*., 2006] that the size and shape of the VCA are influenced by the ability of an observer to resolve the angular separation of the sign (φ in Figure 4.2). The angular separation is dependent on the size of the sign (l in Figure 4.2, or more correctly the size of the letters on the sign), the distance of the observer from the centre of the sign (d in Figure 4.2) and the observation angle (θ in Figure 4.2). The observation angle is defined as the angle subtended by the observers line of sight to a normal line bisecting the surface of the sign. When the observation distance is fixed, an observation angle of 90º (e.g. P_3 views the sign side on. Note that the observation angle is slightly smaller than 90º for better illustration.) results in an angular separation of 0º, effectively making the sign invisible to the observer, while an observation angle of 0º (e.g. P_1 views the sign straight on in Figure 4.2) provides the maximum angular separation.

Clearly, there is a minimum angular separation (φ_{min}) beyond which it is no longer possible to resolve the sign and hence there is a maximum observation angle beyond which it is impossible to detect the sign. In this work, the minimum angular separation (φ_{min}) which can be resolved by the human eye is taken as a constant. For a sign of fixed size with an observer at a fixed distance from the centre of the sign, as the observation angle (θ) increases, the angular separation (φ) of the sign decreases until a maximum observation angle is reached beyond which it is no longer possible to resolve the angular separation of the sign (i.e. $\varphi < \varphi_{min}$). Thus for a sign of given sign size, in order to resolve the angular separation of the sign, as the observation angle increases, the maximum viewing distance must decrease. Similarly, for a given viewing distance there will be a maximum observation angle beyond which the sign cannot be resolved. As the size of the sign increases, both the maximum viewing distance and the maximum observation angle increases.

Thus for an observer to be able to resolve a sign (i.e. make out the individual elements in the sign) at the maximum observation distance, the observation angle should be such that the angular separation of the individual elements making up the sign are greater than or equal to φ_{min}. Taking, for example, the maximum viewing distance for viewing signs with an observation angle of 0º (i.e. straight on) as specified in the NFPA Life Safety Code Handbook, the maximum viewing distance for signs with lettering of 15.2 cm height is 30m. This produces a φ_{min} of 0.29º.

Considering the relative positions of observer P_2 and the sign S depicted in Figure 4.2, in order for this observer to be able to read the lettering on the sign the distance d between P_2 and the centre of the sign must be such that the angle φ is greater than or equal to φ_{min} or 0.29º. Thus as the observation angle θ increases, the distance d must decrease in order to maintain the angular separation of the sign to φ_{min}. By determining the length of distance d within the constraints of the angular resolution of the eye, the visibility catchment area of the sign can then be defined.

An efficient method of determining whether the sign is visible from a particular location within the geometry, given the considerations described above, would be to determine the geometrical shape that is formed by the maximum viewable distance from the sign. In the proceeding section, the geometrical considerations previously discussed are examined in order to determine the nature of the VCA.

The coordinates of the points O, C and D in Figure 4.2 are $O(0,0)$, $C(-\frac{l}{2},0)$ and $D(\frac{l}{2},0)$ respectively. As the line segment OE has to be determined, the point $E(x,y)$ is an unknown. Considering the equation of a line $(y_0 - y_1) = m(x_0 - x_1)$, the line DE is defined by $m_1 = -y \big/ (\frac{l}{2} - x)$ and the line CE is defined by $m_2 = y \big/ (\frac{l}{2} + x)$.

Using the following trigonometric identity

$$\tan(\varphi) = \frac{m_1 - m_2}{1 + m_1 m_2} \qquad \textbf{(Equation 4.1)}$$

and the equations for *DE* and *CE* defined above, one obtains

$$\tan(\varphi) = \left(-\frac{y}{(l/2)-x}\right) - \left(\frac{y}{(l/2)+x}\right) \Bigg/ \left(1 + \left(-\frac{y}{(l/2)-x}\right)\left(\frac{y}{(l/2)+x}\right)\right) = -\frac{yl}{(l/2)^2 - x^2 - y^2}\,.$$

(Equation 4.2)

Then rearranging Equation 4.2 and adding $\frac{(l/2)^2}{\tan^2(\varphi)}$ to both sides of the equation, one obtains

$$(l/2)^2 + \frac{(l/2)^2}{\tan^2(\varphi)} = x^2 + y^2 - 2\frac{y \cdot (l/2)}{\tan(\varphi)} + \frac{(l/2)^2}{\tan^2(\varphi)}\,. \qquad \textbf{(Equation 4.3)}$$

Finally, simplifying Equation 4.3 produces

$$\left(\frac{(l/2)}{\sin(\varphi)}\right)^2 = x^2 + \left(y - \frac{(l/2)}{\tan(\varphi)}\right)^2. \qquad \textbf{(Equation 4.4)}$$

This has the equivalent form of a circle with centre at point $\left(0, \frac{(l/2)}{\tan(\varphi)}\right)$ and radius $r = \frac{(l/2)}{\sin(\varphi)}$.

This circle (M_2 in Figure 4.2) defines the VCA of a sign that is formed of text elements of dimension *l*, assuming a constant angular separation of φ_{min} degrees (or 0.29º derived from the NFPA regulation). In this instance, it is assumed in this calculation that the human ability to resolve vertical components of the sign (i.e. the height of the text) is equivalent to their ability to resolve horizontal components (i.e. the width of the text).

Figure 4.2 depicts the catchment area of sign S generated using the original algorithm (area M_1) – which effectively ignores the dependence of VCA on observation angle. This image is overlapped by the catchment area (area M_2) of the formulation derived above. The restrictions imposed upon the VCA produced by the formulation are clearly evident, as is its circular appearance.

It has to be noted that the theoretical formulation derived here does not produce a circle that is precisely at a tangent to the centre of the sign. Instead, the element (i.e. a letter on the sign) constitutes a chord that intersects the VCA circle as shown in Figure 4.3. In order to illustrate this clearly, the ratio between element *CD* and *h* of the VCA is highly exaggerated. It should be noted that this is not to scale and that in reality the width of the element measured would be much smaller than the diameter of the VCA. Given that the width of this element is significantly smaller than the diameter of the VCA (by a factor of approximately 200), it is assumed that the VCA circle is at a tangent to the sign for the purpose of its calculation (i.e. $t << h \approx 2r$ in Figure 4.3).

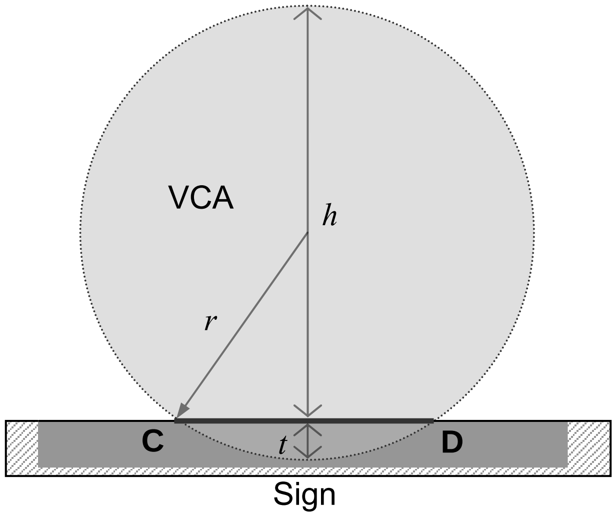


Figure 4.3: The VCA circle is approximately at a tangent to the sign.

It has been shown theoretically that if the ability of an observer to resolve a sign is based on the assumption that the eye can resolve angular separations down to a constant minimum value (irrespective of observation angle), then the maximum viewing distance decreases as the observation angle increases. This is an important result as the regulations implicitly assume that viewing distance is independent of observation angle. Furthermore, instead of the VCA being defined by a semi-circular region, it is noted from the above analysis that the VCA has a *circular* appearance with diameter approximately equivalent to the radius of the previously assumed semi-circular VCA.

In order to validate this theoretical representation of the VCA, a series of experimental trials were designed specifically to study signage legibility distance at different observation angles.

4.3 The Design of the Experiment to Study Signage Legibility Distances as a Function of Observation Angle

4.3.1 The Purpose of the Trials

The purpose of the experimental trials was to test the theory presented in Section 4.2 that the distance from which a sign can be reliably resolved is dependent upon the observation angle. The trials were designed to measure the maximum distance from which individual participants were able to recognise the text (or some portion of it) on the signs for several pre-determined observation angles. The average maximum distances measured were used to outline the actual visibility catchment area of each sign examined.

The reason that the signage legibility distance was measured by reading text rather than by resolving graphical symbol was because the graphical symbol is generally larger and therefore easier to resolve than text. Therefore, the legibility distance measured through the trials represents a conservative estimation.

It should be pointed out that the objective of the design was strictly to examine the relationship between the maximum viewing distance and the viewing angle. The trials were not designed to verify the maximum viewing distance of various types of signs, although the results were also utilised to compare the maximum viewing distance of the same signs estimated by the method suggested by relevant standards [BS 5499 and the NFPA Life Safety Code Handbook]. The impact of the other influencing factors upon the visibility of signs, such as illumination, was not examined. The experiment conditions, including lighting, remained unchanged throughout the trials.

4.3.2 The Setup of the Trials

It would need a very large open area to conduct the trials for participants to approach a sign and identify maximum viewing distance. Not only is it difficult to find such a suitable open area, but it is also difficult to maintain consistent lighting conditions in all directions. To combat these issues, a method was developed to reduce the complexity: instead of letting individual participants approach the sign along different paths as originally planned, they were sent to approach the sign along the same path (a narrow corridor), whilst the angle in which the sign faced was changed every time to make up the pre-determined observation angles. This experimental method allows the maximum signage legibility distances to be examined under consistent lighting conditions irrespective of the observation angle.

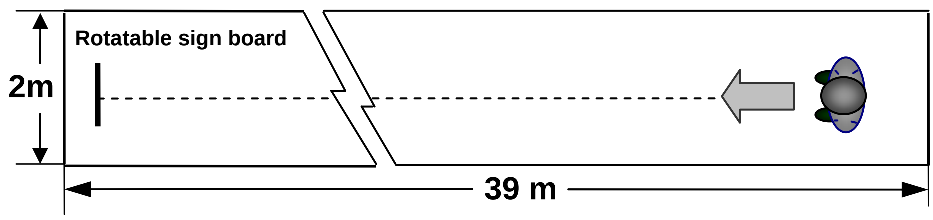


Figure 4.4: The layout of the corridor in which the trials were conducted.

Figure 4.4 shows the corridor in which the experiment was performed. The corridor was 39 metres in length and 2 meters in width. Consistent artificial lumination was provided along the length of the corridor during the trials. A rotatable white board was placed at the left end of the corridor for positioning of the sign. Participants stood at the right end of the corridor at the beginning. They then individually walked along the centre line of the corridor towards the sign board during the trials.

Three standard exit signs which comply with British standard BS 5499 were used during the trials. They are two plastic signs and one photo luminescent sign (see Figure 4.5). These signs vary in the letter size of text, the case of text and the background colour (see Table 4.1). Apart from the size of text, the other differences were not specifically examined in this experiment, as they were not considered to be strong influential factors that affect the relationship between the signage legibility distance and the observation angle. Although the three signs used were of standard designs, it was also felt that a variety of text types and signage designs were required in order to further strengthen the credibility of the results produced.

Sign 1

Sign 2

Sign 3

Figure 4.5: Three exit signs used in the trials.

Table 4.1: The attributes of the three signs used in the trials.

Sign No.	Text on sign	Font	Text height (mm)	Mean text width (mm)	Background colour	Type
1	“FIRE EXIT”	Arial	38	22.5	Light Green	Plastic sign
2	“EXIT”	Arial, bold	66	38.9	Light Green	Plastic sign
3	“Fire exit”	Arial	25 ~ 35	18.0	Dark Green	Photo luminescent sign

These three signs were positioned individually on the rotatable white board at a fixed height of 2 metres to the floor. The observation angle was changed by varying the orientation of the sign on the board to the observer rather than the observer to the sign. For each observation angle the participant walked along the corridor to approach the sign until they could resolve the sign. The average maximum viewing distances measured from the participants reading the signs at different angles are expected to reflect the actual VCA of the sign.

4.3.3 The Experiment Procedure

Prior to the commencement of the trials, participants were asked to prepare for the trial by relaxing from their work for at least 10 minutes, in order for them to acclimatise to the experimental conditions. After this, each individual participant was taken to a lounge area to read a briefing and complete a questionnaire, in order to familiarise themselves with the trial procedure.

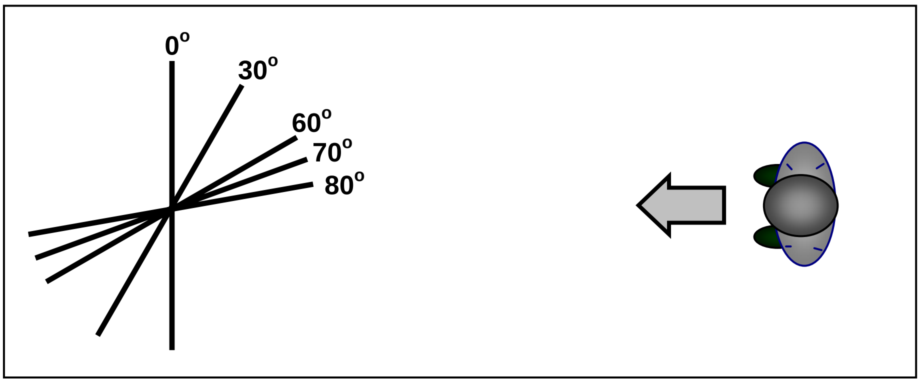


Figure 4.6: Pivoting of the sign to modify the angle in which participant observes the sign.

During the trials the sign board was pivoted successively to five pre-determined angles relative to its initial position, i.e. 0º, 30º, 60º, 70º and 80º (see Figure 4.6). At each position of the sign board, three signs were successively positioned on the board for the participant to read.

Individual participants always started from the far right end of the corridor (i.e. approximately 39m from the sign) and approached the sign slowly along the centre line of the corridor, until they claimed to resolve (i.e. clearly discern) at least half the letters in the sign. The resolution of half of the letters is selected (rather than 100% of the letters) as it was felt that the text (i.e. the words) could be ascertained given 50% of the letters are recognisable. The distances between participants and signs were then measured and recorded.

The individual then continued their approach until they could resolve the full text, in order to demonstrate that the distance recorded for this event is indeed closer than the case when viewing a sub-set of the text. These steps were then repeated for all 15 trial conditions (3 signs × 5 angles) for each participant.

4.3.4 The Participants

The trials were completed by 29 males and 19 females; a total of 48 volunteers. Each of them experienced the same number of experimental conditions. The order in which these conditions were tested was shuffled in a systematic manner in order to minimise the influence of uncontrolled variables, such as learning and tiring. The vision of approximately 55% of the sample required constant correction in the form of spectacles or contact lenses, which were used during the trials.

4.4 Summary

When estimating the visibility of signage, ignoring the angular distortion may result in an overestimation of the visual catchment area of the sign. A theoretical analysis of human eyes resolving the detail on the sign produces a circular representation of the VCA rather than a semicircular representation as previously modelled following the definition of signage visibility limits by relevant regulations. In order to examine the theory, a series of experiment trials were conducted to measure the maximum signage legibility distance at different observation angles. The data collected will be used to produce an empirical representation of the VCA and then compare that with the other two representations. A detailed analysis of the results obtained from the trials is presented in Chapter 5.

Chapter 5

Experimental Results and Validation of the VCA Model

The experiment described in Chapter 4 has been conducted to collect data for studying the relationship between signage visibility distance and observation angle. In this chapter, the data obtained is analysed to produce an empirical representation of the Visual Catchment Area (VCA) of the three signs examined. This empirical representation of the VCA is then compared with the theoretical representation and the original VCA representation modelled, following the definition of signage visibility in relevant legislation and building standards.

5.1 The Experimental Results

5.1.1 The Maximum Viewing Distances at Five Observation Angles

The trials were completed by 48 volunteers, consisting of 29 males and 19 females, with either normal naked vision (45%) or corrected-to-normal vision (55%). Each participant experienced 15 experimental conditions, i.e. three signs at five relative observation angles. The maximum viewing distances (mean value ± one standard deviation) of the three signs when they were observed at five observation angles (in relation to the initial position of the sign board) are listed in Table 5.1 for each of the categories.

Table 5.1: Maximum viewing distances of the three signs at five observation angles.

Mean viewing distance ± σ (m) / Sign No.	Observation angle				
	0°	30°	60°	70°	80°
1	23.38±6.43	21.09±6.13	14.82±4.39	10.12±3.21	5.10±2.06
2	33.11±6.92	30.79±7.11	21.23±6.27	13.64±4.75	6.34±3.11
3	19.84±5.76	18.98±5.49	12.65±4.13	9.04±3.2	4.60±1.97

The results presented in Table 5.1 clearly demonstrate a correlation between the relative observation angle and the maximum viewing distance (mean value) from which the text on the sign can be resolved; for all of the three signs examined, the maximum viewing distance decreases as the observation angle increases. This correlation is more clearly demonstrated in Figure 5.1. It can be seen that the relationship is nonlinear for all three signs; while the shape of the nonlinear relationship curves is similar between the signs.

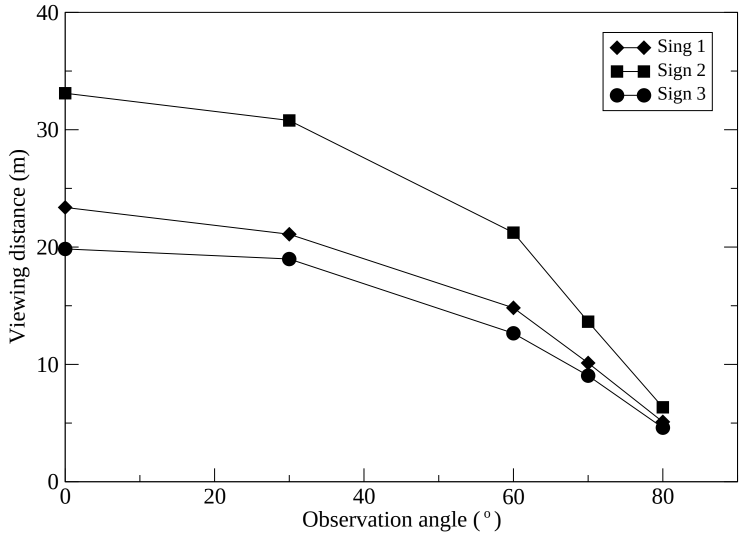


Figure 5.1: The maximum viewing distances of the three signs at five observation angles.

5.1.2 The Visual Catchment Area of the Signs Examined

In order to further examine the correlation between the observation angle and the maximum viewing distance, the data is replotted on a polar coordinate system. The origin represents the location where the sign is fixedly positioned and facing upward, θ (the rotational ordinate) represents the complement of the relative observation angle and r (the radial measurement) represents the distance at which the text on the sign can be resolved. The data is presented in this way in Figure 5.2 for each of the three signs. All of the data-points collected are presented in these diagrams.

For each of the three signs the average viewing distances at the five observation angles are connected by a smooth solid curve generated by curve fitting. A semi-circle with its diameter equal to the average viewing distance measured at the observation angle of zero degree is also plotted as a broken line. It is apparent that although the size of the curves produced in each of these diagrams is different, the shape of these curves is generally similar: the semi-circle is approximated by the solid curve connecting the average viewing distances at the five observation angles.

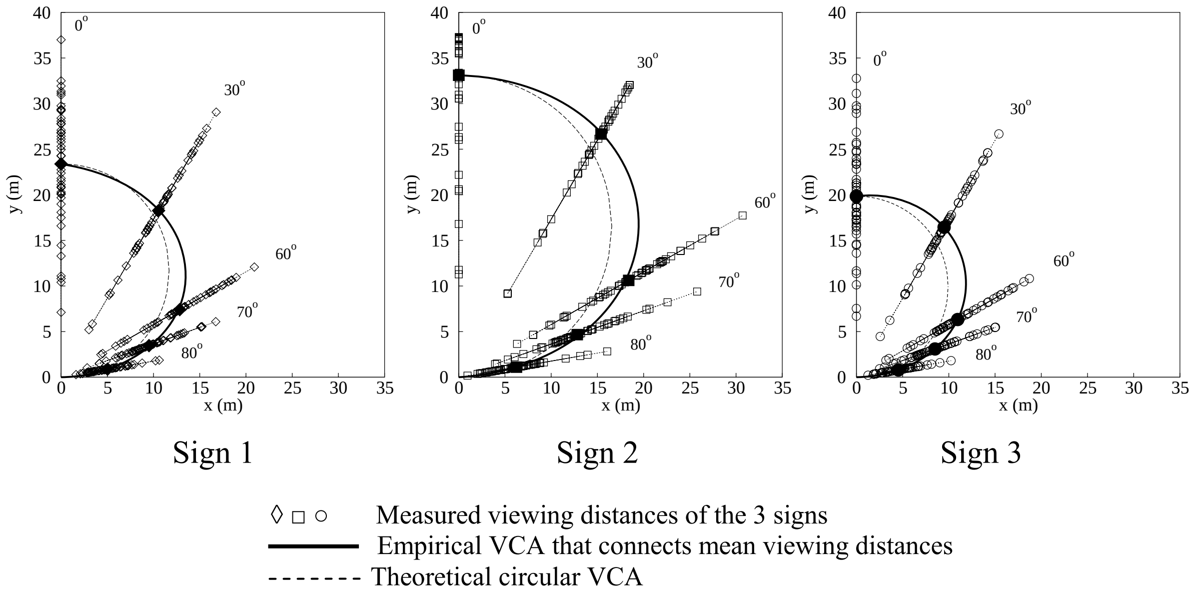


Figure 5.2: The maximum viewing distances plotted on a polar coordinate system.

The similarity of these curves becomes more evident when the maximum viewing distances (mean value) are depicted on the same graph and reflected on the vertical axis to produce an empirical representation of the VCAs (see Figure 5.3). The validity of this operation is based on the assumption that the observational angle is independent of the direction of the approach to the sign (i.e. whether the participants approach the signs from the left or the right side). From Figure 5.3 it is immediately apparent that the empirical VCAs generated for the three signs has a circular representation, or to be precise, a slightly flattened circular representation.

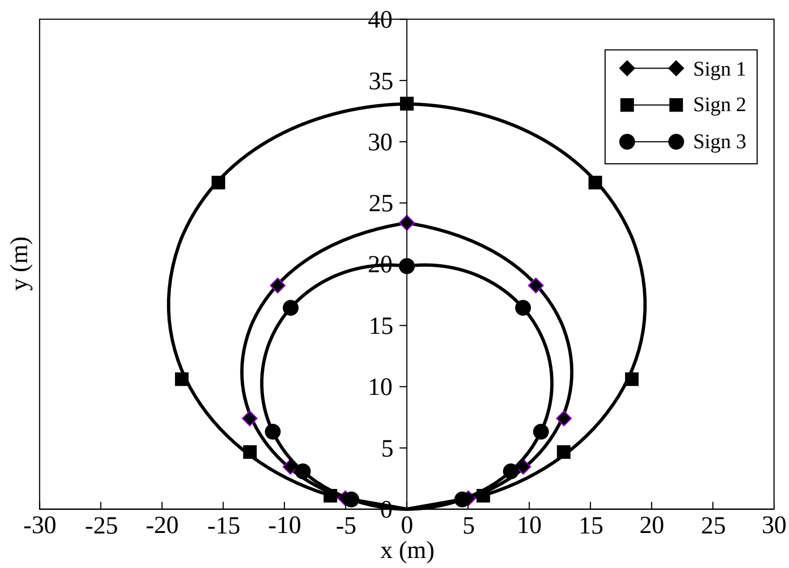


Figure 5.3: An empirical representation of the VCAs of the three signs.

Note that the theoretical VCA has a perfect circular representation based on the assumption that the human eye has a constant minimum angular separation (Section 4.2, Chapter 4). However, the empircal data ploted in Figure 5.2 and Figure 5.3 suggest that the angular separation may be variable. This is clearly illustrated in Figure 5.4 in which the angular separation measured (the ratio of the width of text to the viewing distance) is plotted against the viewing distance. It is apparant that while the data points of the angular separation of each sign remain within a small range, there is a tendency that the angular separation increases with the increase of the viewing distance. It means that the participants' ability to resolve the signs slightly decreases with distance. Considering the way of people resolving a letter, i.e. people need to discern the small details (lines and spaces) of the letter to recognise it, the details can potentially become more cluttered at a long distance than at a close distance, effectively making the letter difficult to resolve. This also explains the overall larger angular separation of sign 2 than the other two signs and the increase of the angular separation of sign 2 even when the distance is reduced, because sign 2 are composed of bold letters which become cluttered more easily than the normal letters on the other two signs, as well as at a close distance.

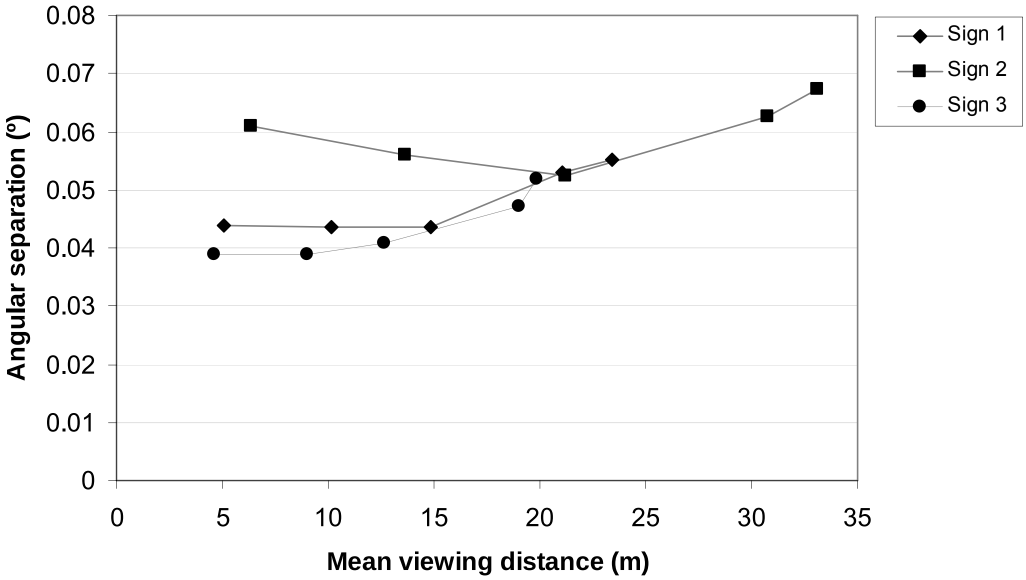


Figure 5.4: The angular separation measured at different viewing distances.

Due to the small variation of the angular separation, the empirical VCAs have a slightly flattened circular representation. The cluttering of the details of lettering with the increase of distance is a factor that contributes to the deviation of the empirical VCA representation from a perfect circle predicted by the theoretical analysis. However, its influence on the shape of the VCA is not as significant as the viewing angle.

5.2 Compare with the Theoretical Representation of VCA and the VCA Outlined by Legislation and Building Standards

In the first edition of BS 5499* the maximum viewing distance (*D*) of exit sign is given by a linear function of the height of the text (*h*) on the sign [Creak, 1997], i.e.

$$D = 250h \qquad \textbf{(Equation 5.1)}$$

This equation is based on the results of eye sight tests which show that people with normal or corrected to normal vision can reliably resolve a detail that subtends an angle of 1 minute. As for resolving text on an exit sign, the number of details in lettering must be taken into account, as well as a small additional margin of extra difficulty in resolving some complex letters. In addition, a safety factor of 2.0 is introduced to produce a conservative estimate of the maximum safe viewing distance, so that most people, including those with lower than normal vision, can still resolve the text on the sign. Finally, the coefficient is rounded off to two significant figures to produce Equation 5.1.

Taking Sign 2 for instance, Figure 5.5 shows a comparison between the empirical representation of the VCA of Sign 2 and two circular VCAs of the same sign based on the theoretical VCA model discussed in Section 4.2, Chapter 4. The maximum viewing distances of the two circular VCAs, i.e. the diameters, are determined according to BS 5499 and the NFPA Life Safety Code Handbook respectively (the safety factor of 2 is excluded in both cases). The height of the text on sign 2 is 66 mm. So the maximum safe viewing distance of Sign 2 predicted by Equation 5.1 is

$$D = 250 \times 0.066 = 16.5m. \qquad \textbf{(Equation 5.2)}$$

This distance is just about half of the average maximum viewing distance, 33.11m, measured for Sign 2 at the observation angle of 0° in the experiment. Considering the correctional factors involved in Equation 5.1 (mainly the safety factor of 2.0), this distance is consistent with the findings of the experimental trials (see Figure 5.5). The angular resolution measured from the experiment is therefore consistent with the value suggested in the formulation of Equation 5.1.

* Since the current BS 5499-4:2000 uses the graphical symbol height to assess the maximum viewing distance of signage, here in this chapter the method in legacy BS 5499 to assess the distance according to the text height is used in order to compare with the experimental results (i.e. the maximum viewing distance measured by resolving text on the signs).

Alternatively, it should be noted that the NFPA Life Safety Code Handbook suggests a viewing distance of 30m for the exit lettering with a height of 15.2 cm. Again if the safety factor and the correctional factors are taken into consideration, this approximates the relationship between lettering height and average maximum viewing distance produced obtained from the experimental trials (see Figure 5.5).

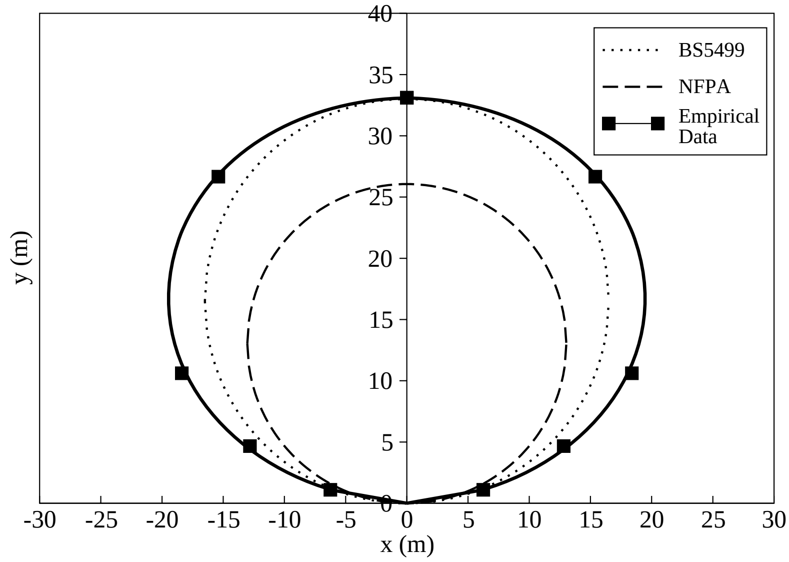


Figure 5.5: The empirical representation of the VCA of Sign 2 and the theoretical VCAs.

Table 5.2 shows a comparison between the average maximum viewing distance of all three signs measured at an observation angle of 0° and the maximum viewing distance as a function of the height of text in these signs based on relevant legislation and building standards. It is apparent that the maximum viewing distances recorded during the trials approximate the values assumed in the NFPA and BS 5499 formulation without the safety factor of 2.0, adding some credibility to the experimental conditions.

Table 5.2: Measured and calculated maximum viewing distances.

Sign and text height (*h*)		Sign 1	Sign 2	Sign 3
		38 mm	66 mm	35 mm
Calculated maximum viewing distance (*D*) as a function of text height with and without safety factor of 2.0	NFPA Life Safety Code Handbook	7.6 / 15.2 m	13.2 / 26.4 m	7.0 / 14.0 m
	BS 5499	9.5 / 19.0 m	16.5 / 33.0 m	8.75 / 17.5 m
Measured maximum viewing distance (mean value) at an observation angle of 0°		23.4 m	33.1 m	19.8 m

Figure 5.6, Figure 5.7 and Figure 5.8 show a comparison between the three representations of the VCAs of the three signs. They are the empirical representation, the theoretical circular

representation and the original semi-circular representation (with and without the associated safety factor) based on the definition of maximum viewing distance in legislation. In each of the three figures, the solid curve connecting the maximum viewing distance (mean value) measured in the experiment represents the empirical representation of the VCA. The circle in broken line represents the theoretical circular representation of the VCA, while the diameter of this circle is set to be equal to the average maximum viewing distance measured at observation angle of 0°. Finally, the semicircles AA' and BB' represent the original semi-circular representation of the VCA base on the maximum viewing distance defined in BS 5499 and the NFPA Life Safety Code Handbook respectively excluding the safety factor of 2.0; while the semicircles CC' and DD' represent the same original semi-circular representation but including the safety factor.

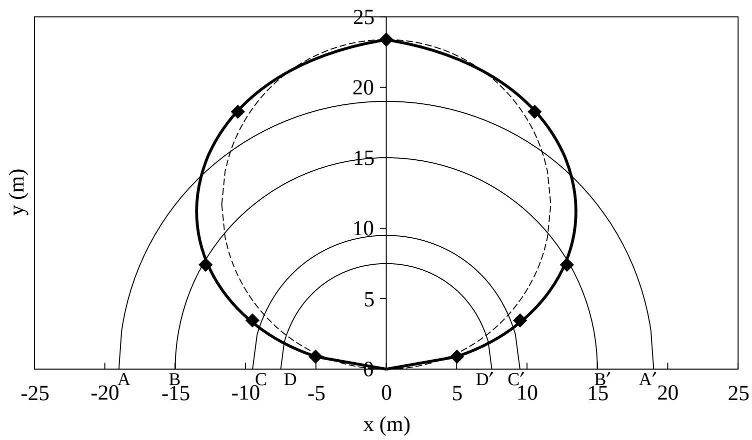


Figure 5.6: Comparison between the three representations of the VCA of Sign 1**.**

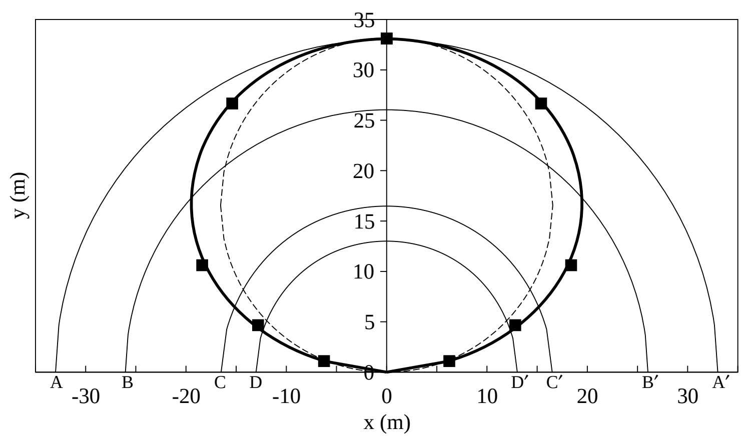


Figure 5.7: Comparison between the three representations of the VCA of Sign 2**.**

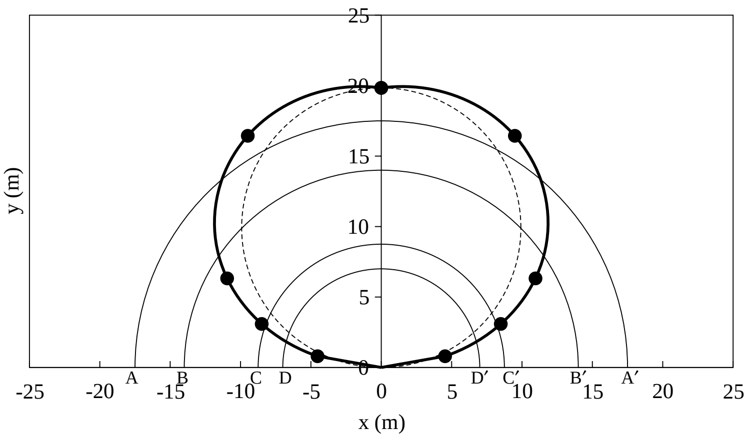


Figure 5.8: Comparison between the three representations of the VCA of Sign 3**.**

It is clear that the empirical VCAs of the three signs are three flattened circles. The original semi-circular VCAs are clearly different from the empirical VCAs. This means that the underlying assumption in the original VCA model (i.e. the maximum viewing distance of a sign is independent of the observation angle) did not correctly address the visibility limits of signage. In contrast, the empirical VCAs are closely approximated by the theoretical circular VCAs with the diameters equal to the maximum viewing distances of the signs approached perpendicularly. This confirms the initial hypothesis that a sign can be seen by an observer from a circular area located at a tangent to the surface of the sign. This is due to the constant nature of the angular resolution of the human eye and the non-linear relationship between the observational angle and maximum distance from which the sign can be resolved. Therefore, applying a slight simplification, it can be assumed reliably that the VCA of a sign is approximated by a circle with its diameter equal to the viewing distance of the sign approached perpendicularly.

Within buildingEXODUS the theoretical model describing the non-linear relationship between observation angle and maximum viewing distance is then implemented to replace the original VCA model. It should be noted that this produces conservative results as it generates a circular VCA with the same maximum radius as the flattened circle generated from the experiment (the VCA circle from theory lies within the flattened VCA circle produced by experiment).

5.3 Summary

The data collected from the experiment described in Chapter 4 is analysed in this chapter. The results clearly contradict the implicit assumption in legislation and building standards that the maximum viewing distance from which a sign can be resolved is independent of the observation angle. In contrast, the results confirm that the maximum viewing distance of the sign decreases as the observation angle increases, while the VCA of the sign is approximated by the theoretical representation of the VCA: a circular area located at a tangent to the surface of the sign with its diameter equal to the viewing distance of the sign approached perpendicularly.

These results are valuable in their own right as they more accurately define the visibility limits of signs. In addition, the method of determining the VCA of signs has been implemented with the buildingEXODUS evacuation model providing a more accurate way of determining the visibility of signs in complex geometries.

The current stage of this study is purely to show the physical aspect of modelling signage in evacuation modelling. In the next stage of the study, the interaction process between occupants and signs will be examined through the design and conduction of the second phase of signage experimental trials, which are then described in Chapter 6.

Chapter 6
Experimental Study and Analysis of the Interaction between Occupants and Exit Signs

6.1 Introduction

Signage systems are widely employed in workspaces and public buildings in accordance with safety legislation and building standards, aiming to provide general information and safety messages to occupants, and assist them in wayfinding during circulation and evacuation. The assumption underlying the provision of signage is that occupants will perceive the signs provided that they are within the maximum viewing distance of the signs defined by relevant legislation and standards. It is further assumed that upon perceiving the signs, occupants will correctly interpret and comply with the safety information conveyed by the signs and make a decision accordingly.

The use of signage as the means to solve the wayfinding problem is reasonably practical if signage systems function as expected. However, despite signage systems being extensively used in various built environments, it is unclear how occupants interact with signage in a realistic situation and to what extent signage systems influence an occupant's decision-making process and their wayfinding behaviour.

Due to insufficient research addressing the interaction between occupants and signs, evacuation models mostly follow the above assumptions. Therefore, the validity of the representation of the interaction with signage in these models is often in doubt. Several cases of fire (Chapter 1) in the past show that the inability to locate escapes route/exit resulted in insufficient use of available means of escape, and most people only tried to escape through the routes they came in or the routes they were familiar with, even when signs were present. This, to some extent, suggests a potential failure of the assumptions concerning the occupant interaction with signage systems. Consequently, not only does the provision of signage systems in buildings require a new view of the effectiveness of signage systems, evacuation models, used in design and assessment process to enforce regulations, also need to correctly simulate the interaction. To address this issue, an experimental approach was proposed to study the interaction and the effectiveness of signage systems.

6.1.1 Interaction between Occupants and Signs

The general process of the interaction between an occupant and a sign happens when the sign is within the perceivable range of the occupant, i.e. the visual catchment area (VCA) of the sign. A successful interaction is the result of a series of actions: approaching the sign, perceiving the sign, interpreting the signage information perceived, decision-making following the interpretation and acting (pursuing new journey). An unsuccessful interaction will result in neglecting the sign and pursuing the original journey if any phase of the interaction fails to proceed [Filippidis *et al.*, 2003, 2006] (see Figure 6.1).

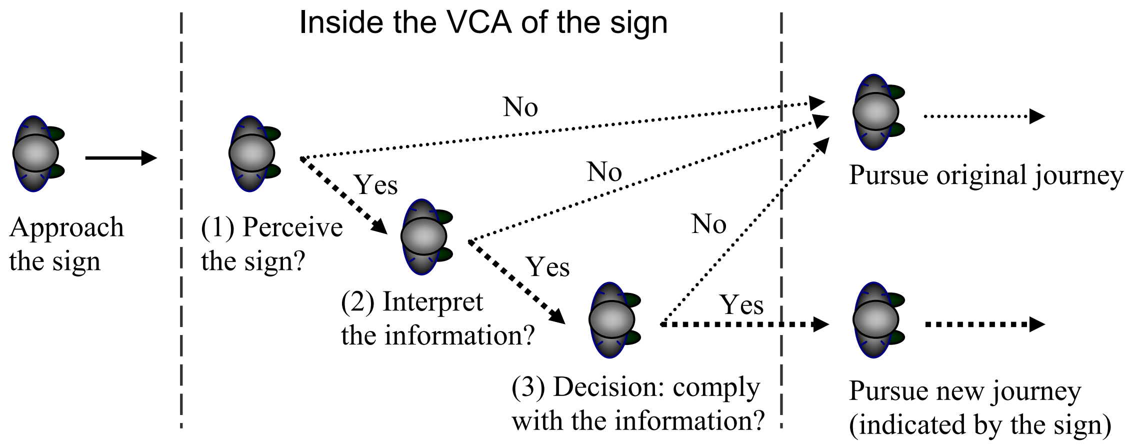


Figure 6.1: The process of the interaction of an occupant with a sign.

The possible interaction starts when an occupant approaches a sign from a distance and the sign falls into the perceivable range of this occupant's eyes; i.e. the sign becomes visible. As the occupant moves on, the relative orientation between the occupant and the sign may vary with the occupant's location and the direction in which they are facing. When the relative orientation allows the sign to be seen, the occupant may perceive the existence of the sign or completely miss the indication of the sign. If the occupant perceives the sign, they may interpret and accept the information perceived and make a decision accordingly, or they may ignore the information based on other considerations. If, on the contrary, the occupant does not notice the sign or ignores the information, they may carry on their original journey. The interaction ends when the occupant eventually exits the VCA of the sign. During this period, whether they actually register seeing the sign or they fail to perceive the sign is influenced by a number of factors relating to the physical, physiological and psychological aspects of the interaction.

First of all, the interactive process requires the sign to be physically visible to the occupant. The visibility of the sign is determined by both physical and physiological factors. The physical factors address the physical aspects of the visibility of the sign including the location of the sign, the internal configuration and the height of the occupant etc [Filippidis *et al.*, 2003, 2006]. The physiological factors address the capability of occupant's eyes discerning the critical details on the sign. In practice, this capability is often represented by the maximum viewing distance that is determined by the size of details on the sign and the visual accuracy (resolution) of the occupant's eyes. The maximum viewing distance is also influenced by the observation angle due to the effect of angular distortion (see Chapter 4 and Chapter 5). The extent within which it is physically possible for the occupant to see the sign is defined as the visibility catchment area (VCA) of the sign for the convenience of modelling [Filippidis *et al.*, 2001, 2003, 2006].

When the occupant is located within the VCA of the sign and is facing in the direction which allows the sign to be seen, it does not necessarily mean the sign will definitely be seen and utilised by the occupant. Whether the occupant registers seeing the sign is subject to their attention given to the wayfinding task and the presence of the other visual stimuli. Even if the occupant does see the sign, how they respond to the information on the sign is influenced by their interpretation of the information, their existing knowledge, objectives and motivations etc.

Finally, after successfully detecting the sign and correctly interpreting the information, the occupant has to decide whether they will comply with the information or ignore it. It requires the occupant to make a decision according to the information perceived and the situation in which they find themselves. For instance, if the sign indicates a shorter exit route than the route leading to their original target exit, it is likely that the occupant will redirect to this new route. Otherwise, the occupant may just ignore the information. It should be noted that the decision may also be influenced by other behavioural considerations, such as familiarity and other people's actions.

The research into the interaction between occupants and signage systems is conducted through two phases of experimental trials. The first phase of the trials (Chapter 4 and Chapter

5) focuses on the visibility limits of signs and aims to identify the area within which it is physically possible for the sign to be clearly seen and read. The second phase of the trials aims to examine the process of interaction and the factors involved. The two phases of experimental trials designed to study the interaction are illustrated in Figure 6.2.

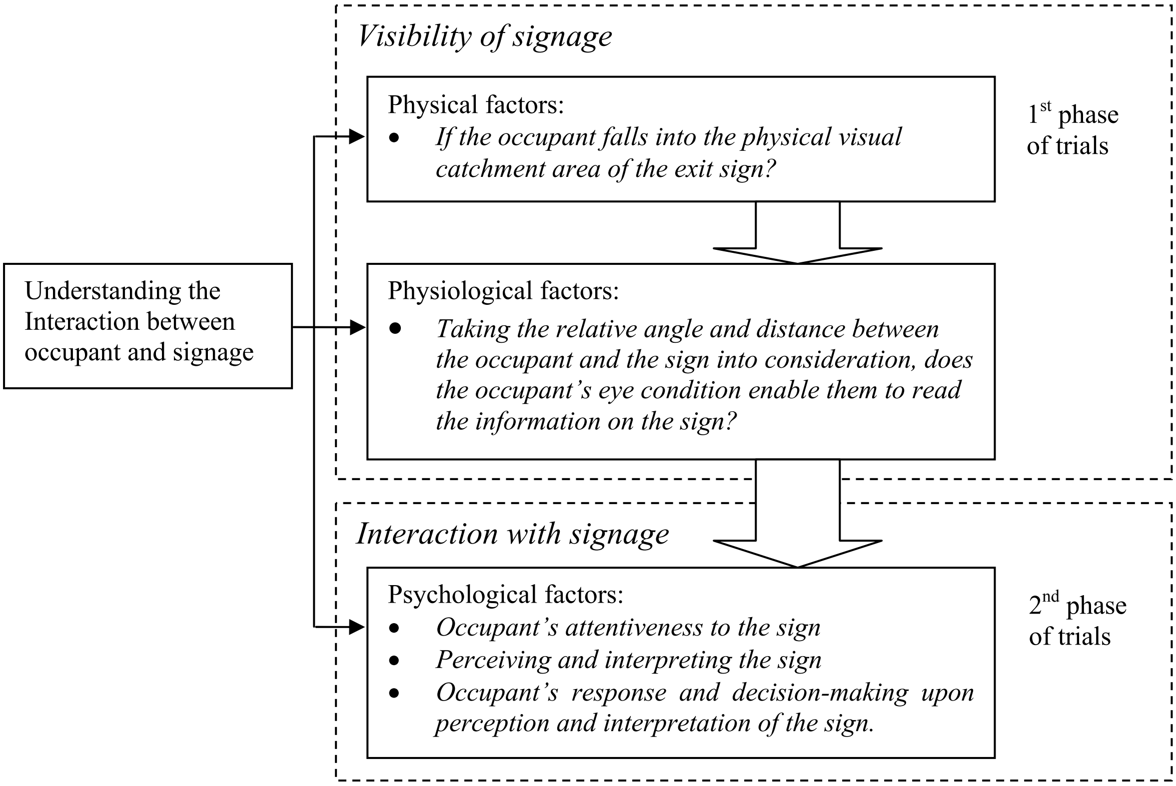


Figure 6.2: The interaction between occupant and signage and the influencing factors.

6.1.2 Effectiveness of Signage System

It has been demonstrated that occupants may not notice or remember the existence of signs available to them [Weisman, 1985; McClintock *et al*, 2001]. Even if occupants register seeing the sign, sometimes they may still not correctly interpret and utilise the information on the sign. Therefore, when assessing the effectiveness of a safety design including signage system, the possibility that the signage system may be under-used must be taken into consideration.

The insufficient use of signage systems, i.e. overlooking and ignoring, could be due to the influence of various factors and the occupant's state of mind. To better understand how these factors influence the effectiveness of signage systems and how an occupant interacts with signage systems an attempt is made via the second series of experimental trials to examine occupants' interactions with signs.

This research was conduced in a carefully selected building (to meet the requirement of examining the pre-defined interaction configurations) and helped by a group of human subjects volunteering in a series of experimental trials. During the trials each participant was required to navigate a part of the building and find a way out solely by their own efforts. Their movement in the building and what they were looking at during the trials were recorded by a head mounted mini video camera designed for the experiment. In addition, a short interview was conducted immediately after each trial to give the participant an opportunity to explain their exit route/exit door selection and the factors which affected them in making a decision at each of the decision points. Since no specific mention of the signage system was made prior to the trials, it is expected that the interactions between participants and signs happen in a natural way that resembles a realistic situation.

6.2 The Design and Procedure of the Signage Experimental Trials

6.2.1 Exit Sign and the Level of Redirection

The signage designation of the direction of an escape route and the location of en exit can be classified into three levels: zero, first and higher level according to the relative distance and position between the sign and the target indicated [Filippidis *et al.*, 2003, 2006] (see Figure 6.3). The sign of zero level is typically positioned adjacent to a target such as exit door and assembly point etc, so that the sign and the target are immediately associated. The sign of first level is normally positioned pointing to a target from a certain distance away. The sign of higher level is similar to the first-level sign, but it points to another sign rather than a target. Thus, occupants need to look in the direction indicated by the first-level and higher-level signs to find the target or another sign indicated. If a sign is not adjacent to the target indicated, it normally requires the sign to be positioned within the maximum viewing distance of the targets [BS 5499-4:2000; ISO 16069:2004].

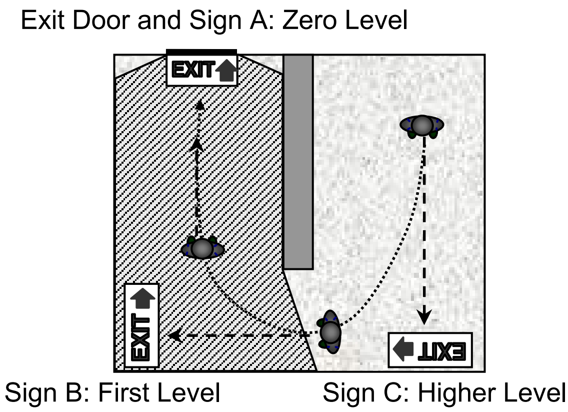


Figure 6.3: Illustration of three levels of signage designation.

It is expected that occupants may easily establish a link between a sign and its target in close vicinity. It will be more difficult for the occupants to connect a first/higher level sign to its target due to larger separation distance. Therefore, the level of signage designation of exit route direction and exit location is considered as a factor investigated in this research.

6.2.2 The Method in which Occupant Approaches Sign

Standing within the VCA of a sign does not guarantee an occupant will perceive the sign. The sign must also be caught in the occupant's field of vision. Therefore, the interaction between occupant and sign is not only influenced by the maximum viewing distance of the sign, but also (1) the human field of vision and (2) the relative orientation between the occupant and the sign.

The human field of vision of is primarily determined by a vertical field of view and a horizontal field of view. The vertical field of view has an average vertical angle of 135° [Werner, 1991] (see Figure 6.4). If head movement is taken into account, the vertical field of view can be even larger. According to British standard BS5499-4:2000, exit signs are recommended to be mounted at a height between 1.7 m and 2.5 m. In Figure 6.4, a sign is positioned 2.5 m from floor level on the right wall. A viewer facing this sign is assumed to be 1.75m tall. The sign is only out of the viewer's vertical field of view when the viewer is within a blind spot of 0.4 m from the wall (a rare condition). Therefore, given the recommended mounting height of signs and the angle of the vertical field of view, it is safe to assume that signs are located within an occupant's vertical field of view in most circumstances.

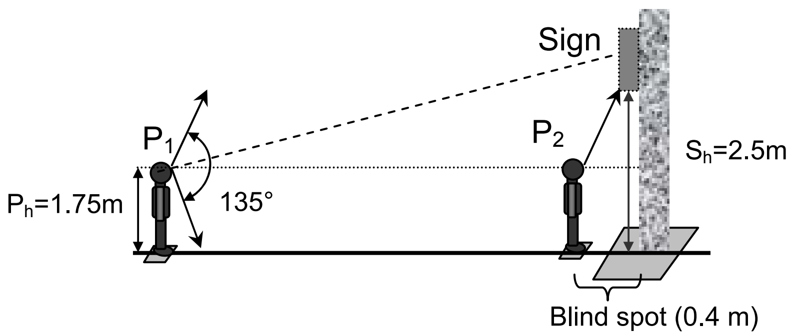


Figure 6.4: The human vertical field of view.

The horizontal field of view of motionless human eyes has an average horizontal angle of 200° [Werner, 1991], which includes a smaller angle of 120° binocular vision (seen by both eyes) [Henson, 1993] (see Figure 6.5). The binocular vision is critical to human visual perception as both eyes need to focus on an object to resolve the detail on it. Similarly, the horizontal field of view can be extended by moving eyes and head from one side to the other side.

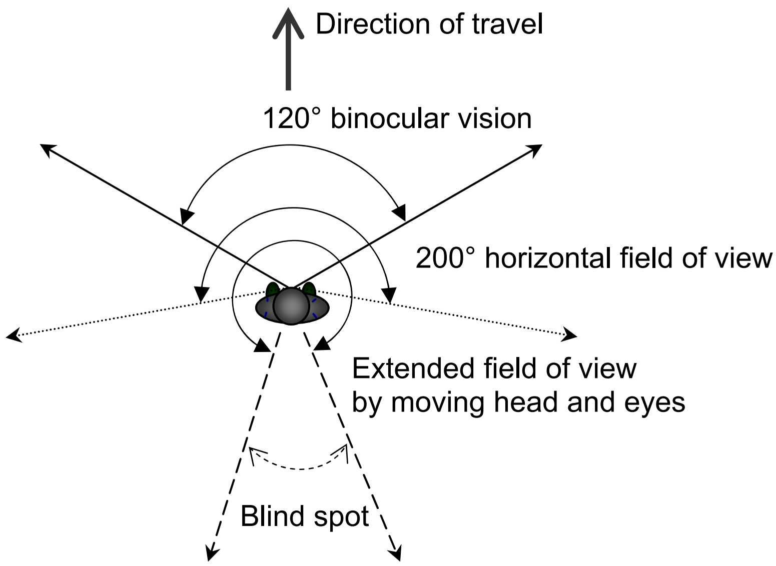


Figure 6.5: The human horizontal field of view (top view).

Despite the vast field of vision, each human eye has only a small central cone of 2 degrees with high visual acuity. In order to get a clear view and read a sign, an occupant must move both eyes towards the sign and focus on it. Therefore, it is not guaranteed that a sign falling in the field of vision will be perceived by the occupant and that the information will be understood. In other words, given the sign is caught in the field of vision, whether this sign is perceived is also influenced by the occupant's direction of travel, head/eye movement and attentiveness (focusing).

Model developers have tried to represent the influence of the relative orientation between occupant and sign upon the likelihood of occupant detecting the sign [Filippidis *et al*., 2003, 2006]. One approach is to impose an arbitrary detection probability on an occupant who falls within the VCA of a sign. Another more sophisticated approach is to assign different detection probabilities according to the relative orientation angle between the occupant and the sign. For example, it is apparently easier for the occupant to detect a sign that is straight in front than a sign that is located at an angle to the line of sight. As a result a relative higher probability is used in the former case than in the latter case (see Figure 6.6). These two approaches are primarily based on engineering judgment as no data has been collected regarding the influence.

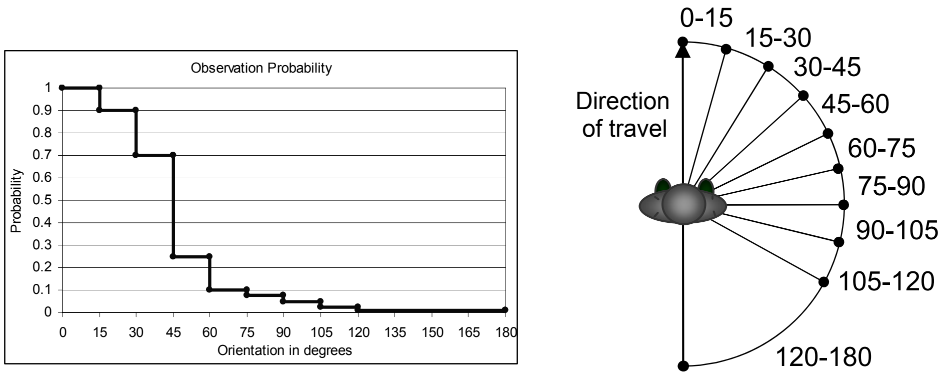


Figure 6.6: The detection probability as a function of the relative orientation. [Filippidis *et al.*, 2003, 2006]

While this research aims at a quantitative estimation of the influence of signage upon people's decision making, in practice there are two obstacles to data collection under experimental conditions concerning the detection probability for viewing the sign at different angles. First, it is difficult to tell exactly when participant detects a sign and measure the relative orientation angle. Second, it is impractical to distinguish between the influence of viewing the sign at different angles upon the detection probability and the influence of the physiological factor such as attentiveness.

In order to facilitate the implementation of the signage experiment trials and make the data collected usable for modelling, the following simplifications were made to bypass these issues. First, the influence of viewing the sign at an angle within the signage model was represented through the original distribution of the detection probability as a function of the relative viewing angle (see Figure 6.6). Second, two common methods of approaching a sign were examined during the trials. One requires the participant to approach the sign at a zero degree angle to the sign normal (see Figure 6.7a) and the other requires the participant to approach the sign at an angle to the sign normal (see Figure 6.7b).

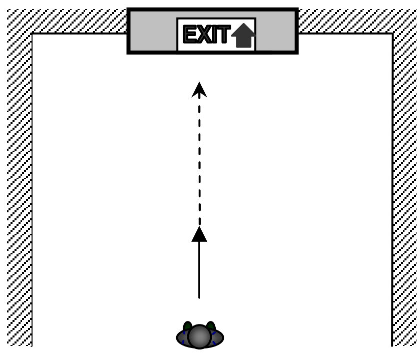
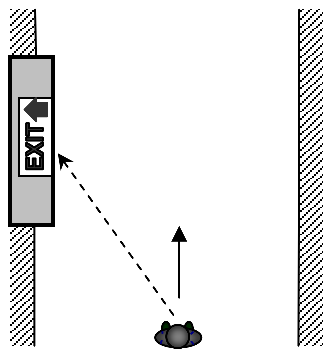
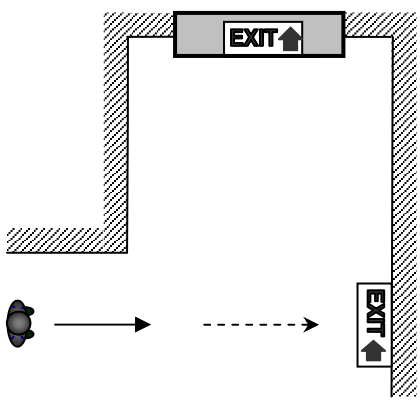
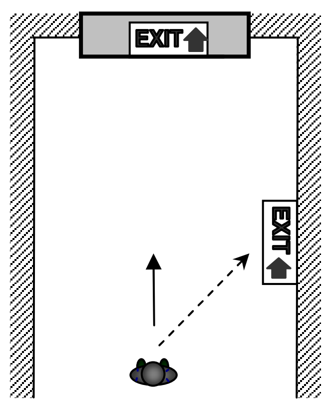
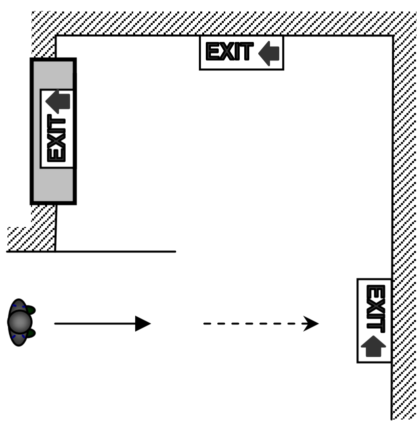
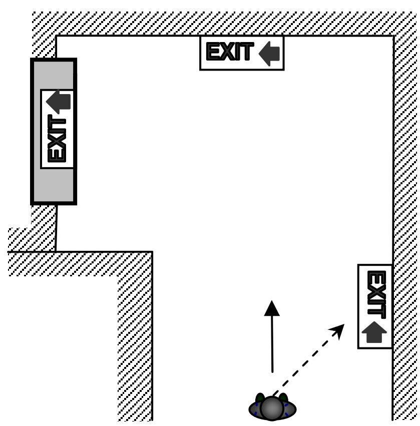
(a) (b)

Figure 6.7: Two methods in which occupant approaches a sign.

6.2.3 Interaction Configurations and Data Collection Points

The combination of three levels of sign (Section 6.2.1) and two methods of approaching the sign (Section 6.2.2) produces a total of six configurations of occupant interacting with the signs. These interaction configurations, S1 to S6, are illustrated in the figures shown in Table 6.1.

Table 6.1: Six configurations of interaction with sign.

	Approach the sign straight ahead	Approach the sign at an angle
Zero-Level		
	S1	S2 (Sign C1/C2)
First-Level		
	S3	S4 (Sign B1/B2)
Higher-Level		
	S5 (Sign A)	S6

It is ideal, but not necessary, to set up and examine all six interaction configurations in the experiment; besides, participants may have difficulty in accurately recalling their decisions and actions on each scene if they were placed in a number of interaction configurations. It was noticed that these six configurations are not equally important to the research and some are similar to each other; therefore, an attempt was made to simplify the design of the experiment by reducing the number of configurations.

Firstly, S1 was abandoned as it is not as important as the other configurations. S1 represents an occupant approaching a target with an associated zero-level sign in the occupant's direction of travel. Regardless of whether the sign is noticed, it is highly likely that the occupant will continue heading for the target. Therefore, it is less important to examine the interaction between the occupant and the sign in S1 than in the other configurations.

Secondly, S3 and S5 are similar to each other because of the similarity between the first-level sign and higher-level sign. In these two configurations, an occupant approaches a first-level sign and a higher-level sign respectively in the direction of travel. The difference is that the sign in S3 indicates an exit with another zero-level sign while the sign in S5 indicates another first-level sign. However, the occupant does not have direct visual access to the target until they turn to the direction indicated by the sign. It makes no difference during the process in which the occupant approaches the sign in the first place. This suggests that it is appropriate to combine S3 and S5, i.e. examining either S3 or S5 in the experiment. Similarly, S4 and S6 were also combined for the same reason that they are similar to each other to some extent.

Finally, the configurations for testing in the experiment were reduced to three: S2, S3/S5 and S4/S6, corresponding to three decision points (see Section 6.2.4) for studying the interaction between occupants and signs.

6.2.4 The Geometry, Exit Route and Exit Signs

The egress trials took place in the Queen Anne Court on the Maritime campus of the University of Greenwich. The building structure was selected since it was readily accessible to the researcher and more importantly, the egress routes provide similar affordances* in terms of lighting, configuration to limit the varieties present for the three interaction configurations mentioned in Section 6.2.3. This building consists of staff offices, lecture halls

* The affordance [Gibson, 1977, 1979; Sixsmith *et al.*, 1988], in the context of evacuation, is the appearance of the corridor which suggests that it is a viable egress route.

and smaller lecture classrooms. The test area used was the circulation area located on the first floor of the west side of the building (see Figure 6.8). The trials were conducted out of term time or out of normal working time so as the trials would not be disturbed by other building users.

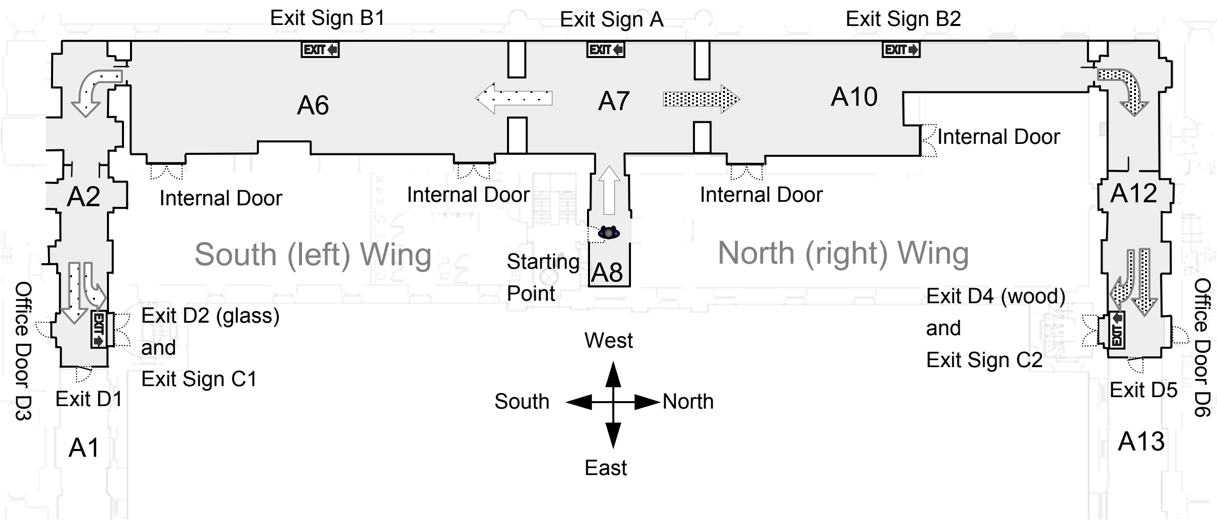


Figure 6.8: The geometry, exit signs and exit routes used in the trials.

The evacuation path involved participants walking down a short corridor (A8 in Figure 6.8) running east-west which ends in a "T" intersection (A7) with the adjoining corridor (A6 and A10) running south-north. The participants then went either left (south) or right (north) along the south-north corridor. Both corridors are approximately equal in length and width. At their widest point, both the north and south corridor are 6.8 m wide. The length of the south corridor is 22.9 m while the length of the north corridor is 22.6 m. Both corridors are more aptly described as open circulation spaces rather than corridors. Although both corridors are viable exit routes eventually leading to two external exits, the left (south) route is more commonly used for circulation as it leads to the main entrance on the south (left) side of the building. On both the left and right side of the east wall of the south-north running corridor are two non-exit interior doors (closed and locked during the trials) leading to rooms. The existence of these non-exit doors can be an interfering factor to unfamiliar occupants. At the south and north extreme ends of the south-north running corridor is a door leading to another corridor running west-east (A2 and A12). The west-east running corridors are approximately 2.6 ~ 3.0 m in width and each of these corridors runs a short distance of 19 m and ends with three doors (closed during the trials), one door across the corridor and two additional doors to either side (see Figure 6.8).

The door across each corridor leads to another stretch of corridor, while in the south (left) wing corridor, the door on the north wall of the corridor is the exit door which has a glass pane and the door on the south wall of the corridor is an office door. In the north (right) wing corridor, the door on the south wall of the corridor is the exit door which is a solid wooden door while the door on the north wall of the corridor is a glass office door. The glass pane in the exit door in the south (left) wing corridor was opaque and obscured the sight of the exit staircase; however, it did let in a considerable amount of light.

It is considered that participants reach the end of the trials once they pass through one of the exit points at either corridor. Participants travel the same distance to reach the final exit and experience a similar series of decision points regardless of the exit route they use.

The egress system thus has three decision points (see Figure 6.8):

(1) the “T” intersection (A7),
(2) the stretch of south-west corridor/circulation space leading from the “T” intersection (A6 and A10),
(3) and the end of each west-east corridor (A2 and A12).

At each of these three decision points emergency signage was available to identify the appropriate path and exit. It is noted that decision points 1 and 2 are similar in that the signs are in essentially open circulation space and the signs indicate an evacuation direction however, the difference between these two decision points is the angle at which the participant approaches the sign. Decision point 3 is considered to be different to the first two decision points as the participant making the decision is in a confined space defined by a narrow corridor, the sign indicates an evacuation exit rather than pointing to an evacuation direction and the egress path ends with three doors in close proximity from which the participant must select in order to continue their evacuation.

The types of sign considered in this experiment are the green “running man” emergency exit signs with directional information (see Figure 6.9). The signs were reflective in nature and the size of the signs located in the corridors and above the target doors are 0.1×0.3 m in size. In all cases the design of the signs complied with UK standards [BS5499-4:2000]. The signs were located in well lit areas illuminated by both natural lighting and artificial lighting. In all signage installation locations, the vertical illumination measured was significantly larger than 100 lux to comply with UK standards [BS5499-4:2000].

(a) in the corridor

(b) above the target door

Figure 6.9: The signs used in the experiment.

The signs vary in the directional information conveyed and the angle at which individual participant approaches the sign. Each sign together with the interaction configuration is introduced in the following sections in the order in which participants encounter these signs.

Exit Sign A at "T" intersection A7:

Participants encounter the first exit sign at A7. A7 is a "T" intersection from where two south-north running corridors leading further away to the left and right side (see Figure 6.10). The two corridors are approximately equal in length and width (see Figure 6.11). Therefore, directional information is required at A7 to help occupants identify the appropriate exit route. Although both corridors are viable exit routes eventually leading to two external exits, the left (south) route is more commonly used for circulation as it leads to the main entrance on the left (south) side of the building. In order to reflect the preference for the left route, the first exit sign, sign A, was positioned in the middle of the white west wall in A7 and the arrow of the sign was pointing to the left towards A6 during the experiment. Within the circulation space of the "T" intersection there were no physical obstructions to hinder participant's progress or block their field of view. There were no other posters or signs in close proximity to sign A.

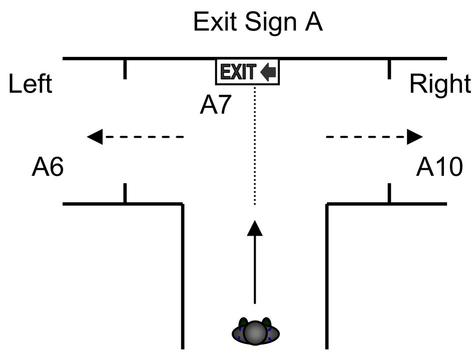


Figure 6.10: Participant at the first decision point at "T" intersection A7.

Left view of the route from the centre of "T" intersection

Forward view of "T" intersection from the starting point (without Sign A)

Right view of the route from the centre of "T" intersection

Figure 6.11: Three views of the "T" intersection.

Sign A is a higher-level sign since it points to the direction in which another sign B1 is located and participants do not have visual access to the other exit routes/doors at the place where they are about to see sign A. In addition, each individual participant approaches sign A straight ahead (see Figure 6.10) so that the interaction with sign A represents configuration S3/S5 in Table 6.1.

Exit Sign B1 at corridor A6 and Exit Sign B2 at A10:

Whether participants went left to A6 or they went right to A10 after leaving A7, they found themselves facing a long corridor running south-north about 23 m in length. The space is mostly empty apart from a few chairs and magazine tables (not shown in the figure) which are aligned along the west wall of the corridor. In each corridor there are two office doors on the east wall leading to internal rooms and one internal exit door at the extreme end. To help participants identify the exit route, two exit signs were positioned in each corridor. One was originally positioned above the internal exit door (D7/D8) and the other one (B1/B2), pointing at the internal exit door (D7/D8), was positioned on the west wall in the middle of the corridor (A6/A10) (see Figure 6.12). As the research was interested in the interaction between participants and sign B1/B2, the two signs above D7 and D8 respectively were hidden from participants during the trials.

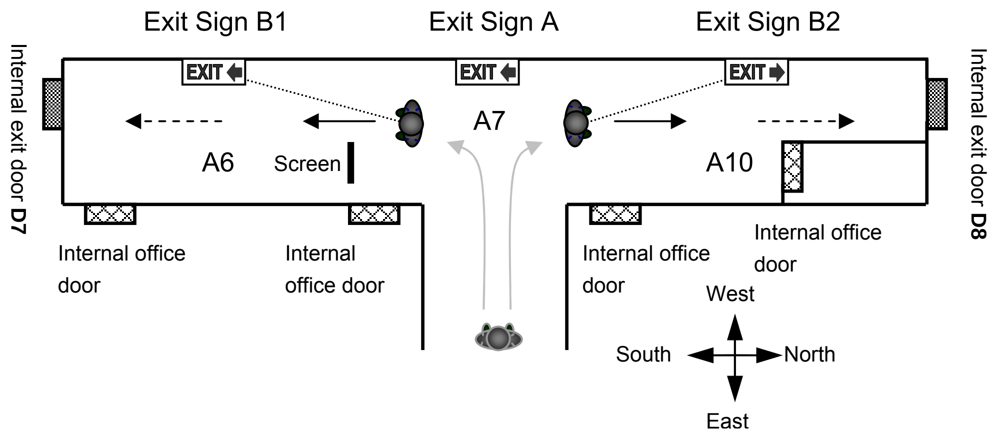


Figure 6.12: Participant at the second decision point at A6 or A10.

Sign B1 and B2 are two first-level signs as they indicate internal exit door D7 and D8 respectively at the south and north extreme ends of the south-north running corridor. Individual participants approached either sign B1 or B2 at an angle to the normal of the sign; therefore, the interaction between participants and sign B1 and B2 represents configuration S4 in Table 6.1.

During their approach to the sign (see Figure 6.13), the relative angle between participant's direction of travel and the sign increases when they become closer to the sign. If participants keep their eyesight straight in the direction of travel, the sign will move relatively from the centre of their field of view to the margin, effectively making the sign more difficult to be detected. On the other hand, the angular span of the contents on the sign, i.e. text and symbol, increases when participants become closer to the sign, effectively making the sign more legible. Therefore, when participants approach the sign, the increase of the viewing angle and the increase of the angular span of the object are two contrary factors that influence the probability of participant detecting the sign. In theory, there should be an optimal point along the path at which it is most likely that participants will detect the sign.

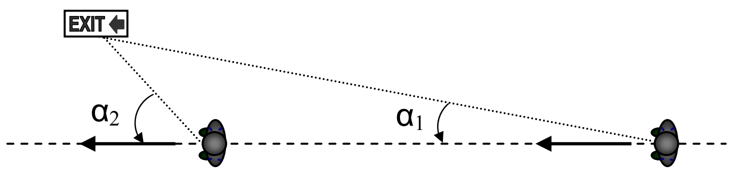


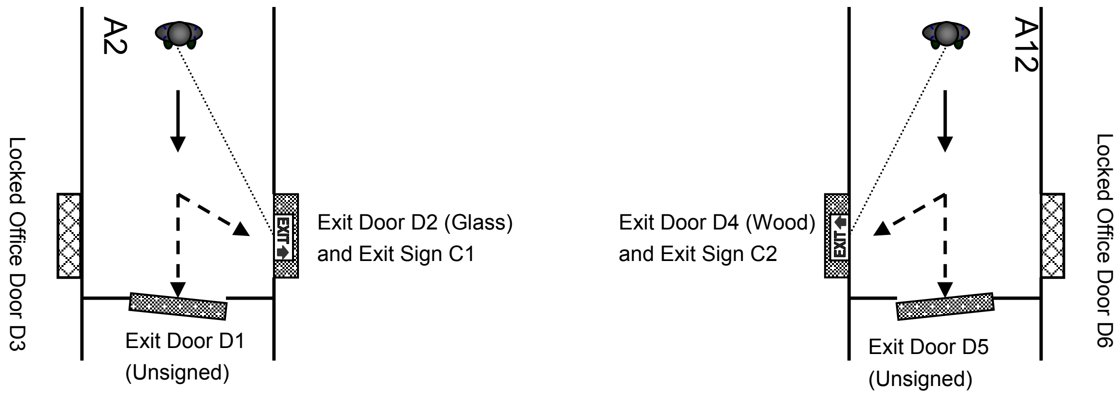
Figure 6.13: Participant approaches the sign at an angle.

The two corridors are similar in configuration in terms of dimensions, position of signage and location of exit doors. So whether participants went through A6 or they went through A10, it was treated as the same scenario during the trials. The data collected was combined in the analysis.

Exit Sign C1 at corridor A2 and Exit Sign C2 at A12:

The last part of the exit route being examined includes two west-east running corridors in the south (A2) and north (A12) wings of the building. A2 on the south and A12 on the north of the building are west-east running corridors that connect the south end of A6 and the north end of A10 respectively. Both A2 and A12 measure about 19 m in length and 2.6 ~ 3.0 m in width. These two corridors are not only of the same dimensions, but also similar in internal configuration in terms of the number and locations of internal doors, exit doors and exit signs. There are several internal offices and office doors along both sides of the corridor, while at the end of each corridor there are three doors: one office door leading to an internal office and two internal exit doors (leading to external exits) for participants to choose from (see Figure 6.14).

The internal exit doors, D1 and D5 in the participant's direction of travel, are leading to an extension of the corridor and stairs to the ground floor. The other two internal exit doors, D2 and D4, are leading to an immediate stairwell directly leading to the outside. D2 and D4 represent a shorter exit route so that they should be considered as the priority choice as compared with D1 and D5. To reflect the priority of D2 and D4 over D1 and D5 two exit signs, C1 and C2, are positioned above D2 and D4 respectively; while D1 and D5 are left unmarked (see Figure 6.14). To differentiate internal exit door D1 and D5 from the other closed office doors, they were left ajar during the trials. It was intended to give participants a hint of accessible exit route behind them, though they were not able to see anything behind the doors if they did not open them.



(a) the south corridor A2 (b) the north corridor A12

Figure 6.14: Participant at the third decision point.

Sign C1 and C2 are two zero-level signs as they were positioned above internal exit door D2 and D4 respectively. An individual participant approached either sign at an angle so that the interaction between participants and sign C1/C2 represents configuration S2 in Table 6.1.

The original plan of the experiment at this stage was to let participants experience the same interaction configuration regardless of whether they go though the south wing corridor (A2) or the north wing corridor (A12). However, it was noticed that exit door D2 and D4 are differently made: D2 is fitted with an opaque glass pane, while D4 is a solid wood door. Although participants were not able to look though D2, the light did come through the windows in the stairwell (see Figure 6.15a). The appearance of D2 may influence participant's interaction with the sign the door, as it may distract their attention and give them an impression that D2 is close to the outside. On the other side, D4 was covered with solid board like the other internal office doors which completely blocked light from passing through (see Figure 6.16c); therefore, there was no such a factor which may distract participant's attention. As a result, S2 was examined separately on each side.

Originally there was an exit sign above exit door D1 in A2 too. As the aim of the research was to examine the interaction between participants and sign C1 at A2, so the sign above the D1 was covered during the trials; thus sign C1 above D2 was the only exit sign at this decision point.

Left view at A2: the glass exit door (signed) on the left and the front wood exit door on the right (a)

Forward view at A2: the front wood exit door (the sign was covered during the trials) (b)

Right view at A2: the front wood exit door on the left and the locked wood office door on the right (c)

Figure 6.15: Three views of the two exit doors and the office door at A2 (the south side).

Left view at A12: the locked glass office door on the left and the front wood exit door on the right (a)

Forward view at A12: the front wood exit door (b)

Right view at A12: the front wood exit door on the left and the wood exit door (signed) on the right (c)

Figure 6.16: Three views of the two exit doors and the office door at A12 (the north side).

6.2.5 Participant Recruitment

The objective of the recruitment of participants was to reflect the general composition of a typical occupancy: students, staff, visitors and residents. Participants were recruited on a voluntary basis. Volunteers were recruited from the local community through newspaper advertising, on the university's website and through word of mouth. There was no restriction in screening the participant population except that they can navigate a built environment by their own efforts and their age must be 18 and over. It was expected that this approach would be able to produce a test population with a broad range of ages, genders, background and experiences.

6.2.6 The Procedure of the Experiment

The procedure of the experiment trials consists of three major steps: preparation, performing the trials and clean up as illustrated in Figure 6.17. The procedure is introduced in the following sections in the order as it is processed.

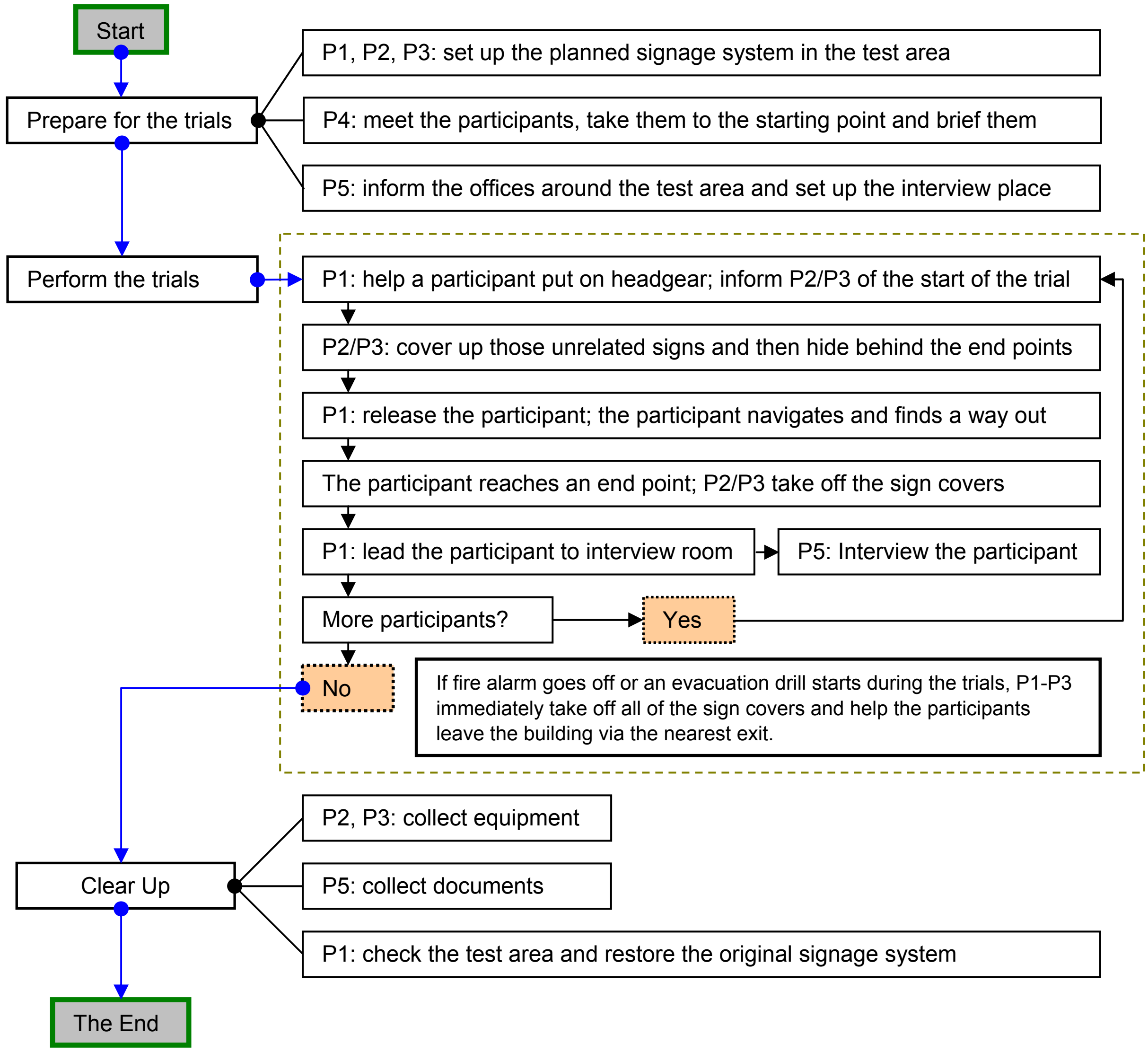


Figure 6.17: The procedure of the experimental trials.

Preparation:

Preparation started half an hour prior to the commencement of the trials. It included four tasks: (1) set up the signage system, (2) test recording equipment, (3) pick up participants and (4) set up the interview room.

At the beginning, 5 exit signs were positioned along the exit routes. They were sign A at "T" intersection A7, sign B1 and B2 at corridor A6 and A10, and sign C1 and C2 at corridor A2 and A12 (see Figure 6.8). Apart from these exit signs the other exit signs, emergency plans and notice boards were covered to reduce the potential influence upon participants.

A member of staff met the coming participants on campus and guided them to the building where the trials were going to take place. Although the building has a symmetric structure, its main entrance is located on the left (south) side. To avoid imposing a first impression about the location of the main entrance upon participants before the trials, the staff member led them into the building through an auxiliary entrance in the middle of the building (a path different to any experimental options). After entering the building participants were held at a refuge area, and then they were briefed about their role in the experiment for the first time (See Appendix A1 and A2). They were also required to finish a short background survey which helped the research identify their experiences and level of familiarity with the premises.

A set of portable video recording equipment designed exclusively for the research was used to supplement data collection. The device included a mini camera mounted on a lightweight helmet and a mini video recorder. Participants wore the headgear and carried the video recorder during the trials. The headgear and the video recorder were tested before the trials.

After the trials participants were given a short interview in order to collect data regarding their decision-making process during the trials. As part of the interview, video footage recorded was played back to help participants recall key events and their decisions. The process of the interview was also recorded to avoid any key notes being omitted by the interviewer. As the final step of preparation, a member of staff set up the interview room and tested the video playback and recording devices.

Performing the trials:

Conducting the trials involved five members of staff working closely together. They are named as P1 to P5 in the following sections. P1 as the key person led the trials and maintained communication with the other four members. P2 and P3 remained at two corridors A1~A5 and A11~A13 respectively to maintain the experimental conditions. P4 remained at the starting point with the other participants waiting for their turns. P5 was in a separate room and prepared for interviewing the participants who completed their runs.

At the beginning of a trial P1 helped a participant put on the portable recording device and informed the other members of the start of the trials. P2 and P3 checked the exit signs, switched on the optional video recording equipment in the corridors and then hid behind door D1 and D5. After they finished these tasks and reached their positions they informed P1 that they were ready. P2 and P3 were also responsible for detaining any unexpected pedestrians during the trials. These people would be temporarily kept away from the experimental area until the ongoing trial finished.

As soon as receiving the notification from P2 and P3, P1 released the participant from the starting point. The participant was then set to find a way out on their own efforts. The participant was free to explore all the possibilities except going back to the starting point. P1 followed the participant at a certain distance behind. If the participant encountered unexpected circumstances, e.g. encountering other pedestrians in the building, or being stuck in a closed enclosure, P1 temporarily held the participant. After solving the circumstances P1 let the participant continue the trial.

The participant eventually reached one of the four exit doors, D1/D2 on the left (south) side or D4/D5 on the right (north) side, since these were the only available exit doors in this part of the building. Either P2 on the left side or P3 on the right side stopped and held the participant on site. P1 from behind helped the participant take off the video recording device and then led the participant to the interview room.

The above process of the experimental trial was then repeated for the next participant waiting at the starting point. The experimental trial was performed on an individual basis, i.e. each participant was required to conduct the trial independently. Although the importance of evacuees communicating with each other is recognised, the design of the experiment does not take into account the influence of participants passing the information conveyed by exit signs to the other participants.

Clean up:

After the experimental trials the premises were restored to their initial state, including moved furniture and the original signage system.

6.2.7 Data Collection

Qualitative data were collected through interviews with participants after each trial. In addition, data collection was supplemented by video footage recorded during the trials.

(a) (b)

Figure 6.18: The portable video recording device and a participant wearing the headgear.

A portable video recording device (See Figure 6.18a) was designed and used in the experiment. The device was composed of a mini camera and a portable video recorder. The viewing angle of the mini camera is about 70 degrees. The mini camera was firmly mounted on a lightweight helmet, which was worn by participants during the trials (see Figure 6.18b). As the camera moved along with a participant's head movement, it continuously captured the participant's forward-facing field of view and head movement in relation to the direction of travel. The video was then saved by the video recorder in a belt bag carried by the participant. Video footage recorded by the headgear was used later in interviews (described in the following paragraph) and analysis (Section 7.2.6, Chapter 7).

Participants were asked to complete a questionnaire accompanied by an interviewer right after attending the trials (see Appendix A3 and A4). The structured interview was conducted in three steps. In the first step a map showing the exit route adopted by the participant was presented. The participant was required to narrate the process of the experiment along the route. Without being asking any anticipated questions, the participant was expected to give an intuitive account of their experiences and decisions made during the trials. In the next step the participant was prompted with five questions. These questions were designed to precisely examine the participant's decisions at the three decision points where the exit signs were installed to provide directional information. The participant was required to identify when and where they made a decision near these points and explain the factors that influenced their decisions. The presence of the exit sign and a few other factors were listed as potential influencing factors; while the participant's own consideration was also recorded. The last part of the interview focused on the interaction between the participant and the exit signs. The interviewer played back the video recorded by the camera worn by the participant during the trials. The video playback was intended to help the participant recall the situation they were faced with during the trials. If they indicated in the previous session that they followed an exit sign, then they were required to identify the moment when they noticed the sign for the first time and also the moment when they responded to the recognition of the sign. If, however, they didn't register seeing the exit sign even the sign had appeared in their field of vision, they were asked to explain what they were concentrating on at that moment. The aim of the questionnaire and interview was to recreate the process of the trials from the participant's narration and to gain an understanding of their decision-making process and the impact of signage on their decisions.

6.3 Risk Assessment and Ethical Approval

This proposed research attempted to collect data relating to the behavioural performance of people interacting with building signage systems. The research included design and conduct a series of experimental trials that required participants to find a way out in a built environment and evacuate by their own efforts. Given that the trials involved human subjects, an application for an approval to conduct this proposed research has been sent to the University of Greenwich Research Ethics Committee. As the main part of the application, risk assessment has been conducted to identify the possible causes of harm and the measures to avoid them (see Appendix A5). This approval was obtained (see Appendix A6).

Apart from the hazards and measures listed in Appendix A5, when fire alarms go off in the building in case of fire or unannounced evacuation drill, the trials will be stopped, while staff members will lead all participants to a place of safety or out of the building immediately.

Participants were given a comprehensive briefing before the start of the trials. The briefing (see Appendix A2) explained in detail the participant tasks involved. It also explained to participants their right to withdraw from the trials at any stage. Finally, their consents to take part in the research were obtained.

6.4 Summary

This chapter describes the experimental trials designed to collect data that would improve the understanding of the interaction between occupants and exit signs. The data is also crucial for evacuation modelling to correctly represent the process of occupant perceiving signs and making exit decision accordingly.

This chapter begins with an analysis of the interaction. It then expands the research question into several influential factors involved in the interaction. Based on the analysis of these factors, the design of the experimental trials is explained together with the data collection method. Finally, as this research involves human subjects, the potential ethical issues are analysed and addressed in the application submitted to the Research Ethics Committee. The approval to conduct the experiment from the Committee is also presented. Chapter 7 will present the experimental results and analysis of the data collected.

Chapter 7
The Results from the Experimental Study of the Interaction between Occupants and Exit Signs

This chapter describes the data collected from the second phase of the signage experiment and data analysis results. The analysis focuses on the influencing factors previously identified in the design phase of the experiment (Chapter 6). The findings will be incorporated into the development of a new signage model (Chapter 8).

7.1 Nature of the Data Collected

7.1.1 Influencing Factors Involved in the Interaction between Occupant and Signage

The interaction between occupants and signage is influenced by a variety of factors, which address the physiological, physical and psychological aspects of the interaction respectively. More specifically, the physiological factor addresses the nature of the observer's eyesight, while a combination of the physiological and physical factors determines the area within which it is physically possible for the observer to receive information from the sign. The psychological factor addresses the observer's perception, interpretation and acceptance of the sign within the visible range, i.e. how they detect the sign and interpret the information conveyed by the sign, and finally, after perceiving the sign, how the observer responds to the information.

Apart from the factors mentioned above, there are some other control factors that potentially influence the outcome of the experiment. Such factors include participant's background, age, gender, the level of stress imposed on them, the grouping behaviour, the degree of familiarity with the building layout, the method in which participant approaches the signs and the level of directional information conveyed by the sign. Although it is possible to design and conduct an experiment to examine all these factors, it is considered to be unnecessary due to the enormous effort required; besides, these factors are not equally important to the understanding of the interaction and modelling. For instance, it is assumed that a participant's background, age and gender would have a minor impact on the outcome as compared with the other factors; therefore, their influence on the results is negligible at the current stage of the experimental research. Some other factors like the level of stress imposed on the participants and the grouping behaviour are unable to be examined under the current experimental design and configuration. Therefore, they are also excluded from the analysis and left for future research. It should be noted that although the level of stress imposed on the participants is not examined, the design of the experiment does try to impose a certain pressure on the participants by putting them through a supposed evacuation scenario (see the briefing given to the participants in Appendix A2). The other factors i.e. participant's degree of familiarity with the building layout, the method in which the participant approaches the signs and the level of directional information conveyed by the sign are assumed to have a significant impact on the interaction between the participants and the signs (Chapter 6). Therefore, they are selected as the key control factors of the experiment and are examined in the following analysis.

7.1.2 The Forms of Data Collection

Three forms of data were collected in the experiment. The first is the video footage recorded during the trials. The other two are the participants' narrations of their experiences and their responses to the questions posed to them during the interview conducted after the trials. The data collected reveals the participants' interaction with the signs in the following aspects:

- Whether they perceived any exit sign(s) positioned at the decision points or they missed them.
- If they did, when and where they noticed the sign(s).
- How the information perceived from the sign(s) influenced their exit route/door selection.

The analysis focuses on the difference in the percentage of participants perceiving, interpreting and utilising the signs in the three interaction configurations (Section 6.2.4, Chapter 6).

7.1.3 Participants and Their Level of Familiarity with the Building Layout

In total 68 test subjects volunteered to take part in the experimental trials. The subject population has a broad distribution of background (see Table 7.1), age (see Table 7.2) and gender (see Table 7.3). It was aimed that the subject population used could represent a general population that would normally be found in the built environment of a university building.

Table 7.1: Breakdown of participants by identity.

	Student	Staff	Visitor	Local resident	Total
Number of participants	32	11	13	12	68
Percentage	47.1%	16.2%	19.1%	17.6%	100%

Table 7.2: Breakdown of participants by age.

	18-20	20-30	30-40	40-50	50-60	60-70	Over 70	Total
Number of participants	2	43	10	6	3	2	2	68
Percentage	2.9%	63.2%	14.7%	8.8%	4.4%	2.9%	2.9%	100%

Table 7.3: Breakdown of participants by gender.

	Female	Male	Total
Number of participants	36	32	68
Percentage	52.9%	47.1%	100%

According to previous work [Sime, 1985; Benthorn & Frantzich, 1999; Shields & Boyce, 2000], route familiarity is a factor in escape route selection. It is assumed that familiarity may affect occupant's attentiveness to wayfinding clues and consequently influence their use of signs during an evacuation (Section 2.1.2.2, Chapter 2). To examine this potential influence, the participants were categorised according to their degree of familiarity with the building layout. Three degrees of familiarity were identified.

1. Unfamiliar participants: those who have never been to the building prior to the trials.
2. Partly familiar participants: those who have been to the building occasionally before.
3. Familiar participants: regular users or visitors of the building.

As there were relatively fewer familiar participants recruited than unfamiliar participants, partly familiar participants and familiar participants are not strictly distinguished. Thus participants who are partly familiar and familiar with the building layout are combined into one familiar group (see Table 7.4). The behaviours of these two groups of participants are examined separately in the following analysis.

Table 7.4: Breakdown of participants by degree of familiarity.

	Unfamiliar	Partly familiar	Familiar	Total
Number of participants	41	20	7	68
Percentage	60.3%	39.7%		100%

7.2 Analysis of the Dataset Collected from the Experiment

The analysis of the data collected is conducted in the order in which the participants encountered the three decision points and exit signs in the trials.

7.2.1 Decision Point 1: Exit Sign A, Route Selection at "T" Intersection A7

The first decision point encountered is A7 and the first sign encountered is sign A (see Figure 7.1). According to the design of the experiment (Section 6.2.4, Chapter 6), interaction configuration S3/S5 (see Tablet 6.1, Chapter 6) was examined at A7.

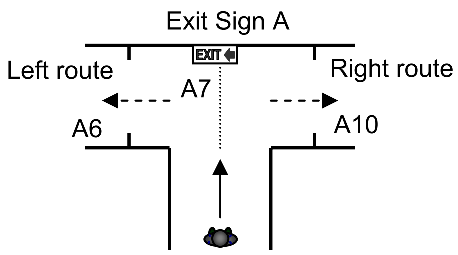


Figure 7.1: Decision point 1: Exit Sign A, route selection at "T" Intersection A7.

The left exit route via A6 and the right exit route via A10 are similar but not identical in structural configuration and dimensions. However, it is expected that the two exit routes offer the same level of affordance to unfamiliar participants if additional information in the form of signage is not available. The expectation is tested by considering the behaviour of those unfamiliar participants who did not detect sign A. Whether participants detected a sign was determined primarily from the questionnaire. Participants were specifically asked in the questionnaire whether they noted a sign at the decision point and whether the sign influenced their decision. In addition, by viewing the video recording of each participant's progress, it is often possible to determine whether a participant noted the presence of the sign.

From this analysis, 25 (61%) unfamiliar participants failed to detect sign A and therefore did not use signage to make a route choice at A7. Of these, 12 (48%) selected the left route and 13 (52%) selected the right route. If the route decision was unbiased and down to random choice i.e. no influencing factor is dominant in the route decision, a balanced choice would be expected between the left and right route. The results for the unfamiliar participants support the view that the affordance of both routes is almost identical.

A similar analysis is undertaken for the familiar group. It was found that 18 (67%) familiar participants failed to detect sign A and therefore did not use signage to make a route choice at A7. Of these, 12 (67%) selected the left route and 6 (33%) selected the right route. It is noted that twice as many of the familiar group elected to go left as went right. While the difference between the familiar and unfamiliar groups is not statistically significant ($\chi^2(1, N=43)=1.48$, $p=0.22>0.05$), the difference between the two groups is consistent with the fact that the familiar group represented participants who had a partial or total familiarity with the building layout and hence were familiar with the fact that the main entrance is accessed via the left route. Indeed, based on the post trial questionnaire, it was noted that 10 out of the 12 participants in the familiar group who went left made the route decision primarily based on their understanding of the building layout.

Table 7.5: The route selection at A7 by those who did not use any exit sign.

	Participants and their route selection		
Unfamiliar participants	25	Who went to the left (A6)	12 (48%)
		Who went to the right (A10)	13 (52%)
Familiar participants	18	Who went to the left (A6)	12 (67%)
		Who went to the right (A10)	6 (33%)

It appears that the nature of the two routes do not bias unfamiliar participant's route choice at A7. This choice is biased among the familiar participants who preferred the left route through A6 to the right route through A10. This preference is consistent with the fact that the main entrance is located at the left wing of the building and the left route is more commonly used for circulation.

Among the 41 unfamiliar participants who entered the "T" intersection, 16 (39%) claimed that they saw an exit sign. Of these, 12 (29%) confirmed that the exit sign they saw was sign A, while the other four could not recall if the sign they saw was sign A. Given the route decisions that they made and given that all 16 (100%) participants stated that their route selection was primarily based on the information provided by the sign, it is most likely that the sign they saw was A or possibly B1 (it is unlikely to be sign B2 as this would have lead them in the other direction). Thus it is can be concluded that all 16 (100%) of the participants who saw sign A correctly interpreted and decided to follow the information conveyed by the sign.

Among the 27 familiar participants who entered the "T" intersection, 9 (33%) claimed that they saw sign A. Upon detecting the sign, all 9 (100%) participants correctly interpreted the sign and decided to move in the direction of the sign. However, the manner in which the familiar participants used the sign information is slightly different from that of the unfamiliar participants. Among the 9 familiar participants, 7 claimed that they made a route selection primarily according to the information gained from the sign, while the other two used the sign information to confirm their route choice which was primarily based on their familiarity with the building layout. It is noted that while the signage detection probability is different between the familiar and unfamiliar participants, this difference is not statistically significant ($\chi^2(1, N=68)=0.23$, $p=0.63>0.05$).

Table 7.6: The route selection at A7 by those who saw sign A.

	The number of participants who saw an exit sign at A7		
Unfamiliar participants	16	Who followed the sign	16 (100%)
		Who didn't follow the sign	0 (0%)
Familiar participants	9	Who followed the sign	9 (100%)
		Who didn't follow the sign	0 (0%)

The results from the experiment can be summarised as follows, for participants who are within the VCA of an emergency exit sign measuring 0.1 × 0.3 m and whose direction of travel makes a 0^o angle to the sign's normal (i.e. moving directly towards the sign):

- 39% (16/41) of participants unfamiliar with the building layout, 33% (9/27) of participants familiar with the building layout and 37% (25/68) of the entire sample (i.e. a population with mixed building layout familiarity) are likely to detect the sign;
- 100% (16/16) of participants unfamiliar with the building layout, 100% (9/9) of participants familiar with the building layout and 100% (25/25) of the entire sample (i.e. a population with mixed building layout familiarity) who detect the sign correctly interpret and follow the information conveyed by the sign.

It can be seen that despite the balanced choice (equal affordance) between the left and right routes at the "T" intersection, signage is the most important determinant of route selection to those who perceived the emergency exit sign. Participants unfamiliar with the building layout had a slightly higher probability of detecting the sign. This is probably due to these participants being more actively involved with searching for signage information due to their unfamiliarity with the layout. Furthermore, in situations where participants had some knowledge of the building layout, while they primarily used their knowledge, signage served to positively reinforce their wayfinding decisions.

7.2.2 Decision Point 2: Exit Sign B1/B2, Route Selection at Corridor A6/A10

The second decision point the participant encountered is corridor A6/A10 and the second sign encountered is sign B1/B2 (see Figure 7.2). According to the design of the experiment (Section 6.2.4, Chapter 6), interaction configuration S4 (see Tablet 6.1, Chapter 6) was examined at A6 and A10.

The two doors located on the east wall of corridor A6/A10 (leading to rooms) complicate the wayfinding as participants may mistake these as being part of the exit route. Sign B1/B2, placed on the west wall opposite to the non-exit doors (no other posters or signs in close proximity), point to the south and north end of the corridor respectively. They are intended to direct the participants to move towards the door at the far end of the corridor. However unlike sign A, which participants approach at a 0^o angle to the signs normal (i.e. moving directly towards the sign), participants approach the B1/B2 sign at a non-perpendicular angle making this sign potentially more difficult to detect. In essence, there are two reasons for the increased difficulty in detection. Firstly, participants must be closer to the B1/B2 sign compared to sign A, before they can discern the information on the sign (i.e. are within the VCA of the sign). Secondly, as the trajectory of the participants is at a non-perpendicular angle to the direct line of sight to the sign, potentially there is a smaller probability that the sign will be detected compared to the situation where participants head directly towards the sign [Sixsmith *et al.*, 1988; Filippidis *et al.*, 2003, 2006]. As both sections of the south-north corridor are similar, the analysis of the participant behaviour in both corridor sections can be combined.

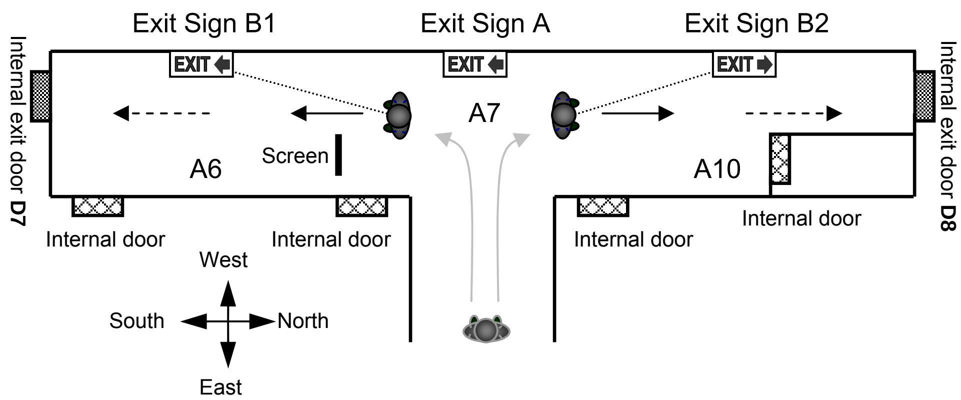


Figure 7.2: Decision Point 2: Exit Sign B1/B2, route selection at Corridor A6/A10.

Among the 41 unfamiliar participants, 15 (37%) claimed that they detected sign B1/B2 at A6/A10. Upon detecting the exit sign, 14 (93%) participants confirmed that the sign had a direct impact on their exit route decision. On detecting the sign, either they made a decision to follow the sign and headed directly towards the door at the end of the corridor or they were encouraged by the sign to continue their journey towards the door at the end of the corridor. One participant stated that noticing the sign had no effect on his route decision and he simply decided to keep on going in the direction he was travelling in. From the video footage it is clear that some participants who did not detect the exit sign B1/B2, mistook the internal doors on the east wall of the corridor as part of the egress route and attempted to pass through these doors.

Among the 27 familiar participants, 7 (26%) claimed that they detected sign B1/B2 at A6/A10. Upon detecting the exit sign, 6 (86%) participants confirmed that the sign had a direct impact on their exit route decision i.e. either they based their decision according to the sign or they were encouraged to continue their journey towards the door at the end of the corridor. One participant stated that noticing the sign had no effect on his route decision and he simply decided to keep on going in the direction he was travelling in. Although the signage detection probability is different between the familiar and unfamiliar participants, this difference is not statistically significant ($\chi^2(1, N=68)=0.85, p=0.36>0.05$).

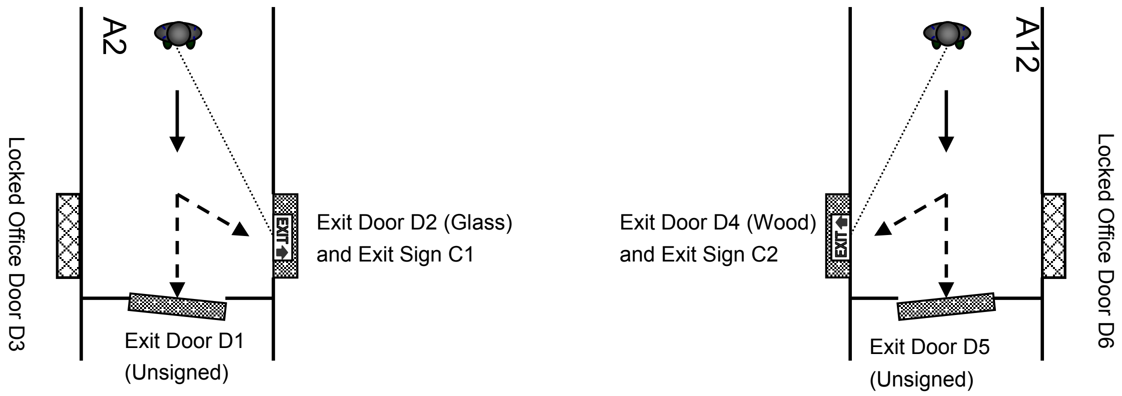
The results can be summarised as follows, for participants who are within the VCA of an emergency exit sign measuring 0.1 × 0.3 m and who approach the sign at a non-perpendicular angle:

- 37% (15/41) of participants unfamiliar with the building layout, 26% (7/27) of participants familiar with the building layout and 32% (22/68) of the entire sample (i.e. a population with mixed building layout familiarity) are likely to detect the sign;
- 93% (14/15) of participants unfamiliar with the building layout, 86% (6/7) of participants familiar with the building layout and 91% (20/22) of the entire sample (i.e. a population with mixed building layout familiarity) who detect the sign correctly interpret and follow the information conveyed by the sign.

Furthermore, in situations where the participant had some knowledge of the building layout, while the participant primarily used their knowledge of the building layout, emergency signage served to positively reinforce their wayfinding decisions.

7.2.3 Decision Point 3: Exit Sign C1/C2, Exit Route Selection at Corridor A2/A12

The third decision point encountered is A2/A12 and the third sign encountered is sign C1/C2 (see Figure 7.3). There are three doors to choose from at the east end of A2/A12, one directly in the path of travel and two to either side. The correct exit door is one of the doors to the side which leads to the emergency stair case. According to the design of the experiment (Section 6.2.4, Chapter 6), interaction configuration S2 (see Tablet 6.1, Chapter 6) was examined at A2 and A12.



(a) Exit Sign C1, exit route selection at Corridor A2 (b) Exit Sign C2, exit route selection at Corridor A12

Figure 7.3: Decision Point 3 at (a) A2 and (b) A12.

While both exit routes along the south and north west-east running corridors are almost identical, there is a difference in the configuration of the final three doors. The emergency exit door D2 (with sign C1) in the south corridor A2 has an opaque glass pane which, while not transparent, is different to the other two doors which are of wooden construction. The emergency exit door D4 (with sign C2) in the north corridor and the non-emergency exit door D5 are both solid wood doors, and the third door D6 is a locked office door with transparent glass pane. The different appearance of these two emergency exit doors may have an impact on participant exiting decision and so it was not possible to simply combine the results from these two doors with signage. This observation was verified through the participant questionnaires which suggested that half the unfamiliar participants using the south corridor who correctly selected the exit door did so due to its physical appearance i.e. the light coming through the door, and not because of the signage. In comparison, all the unfamiliar participants using the north corridor who correctly selected the exit door did so due to the emergency exit sign above that door. Thus different factors were influencing the participants at either door. This means that the data from the south and north wings must be analysed separately.

7.2.3.1 Exit Sign C1, Exit Selection at South Corridor A2

In total 43 participants selected the south corridor in the experiment. Among them 23 are unfamiliar participants and the other 20 are familiar participants. At the east end of A2 the participants were faced with three doors: the emergency exit door D2 with sign C1, the non-emergency exit door D1 and the locked office door D3 (see Figure 7.3a). Figure 7.4 shows how these participants made an exit selection from the available exit doors in the trials.

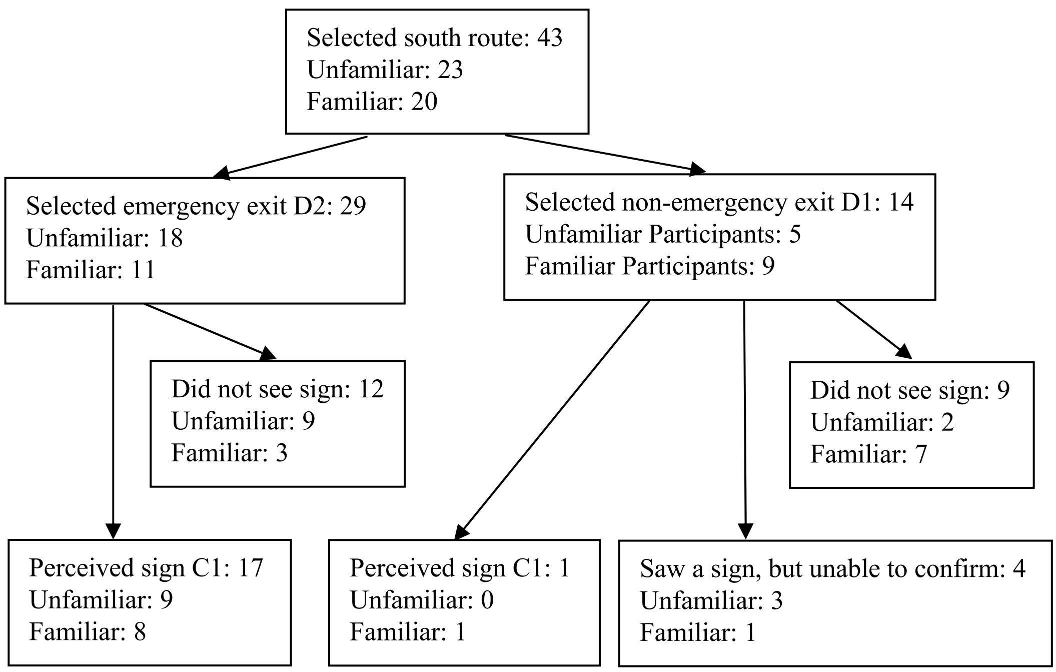


Figure 7.4: Participants' route selection at A2 on the south side of the building.

The analysis of the participant's route selection is processed in the same way as it has been done in Section 7.2.1. Firstly, the participants' exit selection without the interaction with exit sign is examined. Secondly, given the participants' preference obtained from the analysis, the impact of exit sign upon those who detected the sign is examined.

Among the 23 unfamiliar participants who entered A2, 11 (48%) claimed that they did not notice exit sign C1. Among them, 9 (82%) chose to go through the emergency exit door D2 and the other 2 (18%) chose to use the corridor door D1 in the path of travel. It is apparent that exit door D2 is considerably more attractive than exit door D1 to those who are not familiar with the building layout and did not use signage. This is most likely because the glass on the top half of exit door D2 allows light to come through, which gives an impression to the participants, that it may provide a direct route to the exterior, hence increasing the affordance of the door.

Among the 20 familiar participants who entered A2, 10 (50%) claimed that they did not notice any exit sign. Among them, 3 (30%) chose to escape through the emergency exit door D2, while the other 7 (70%) chose to use the corridor door D1. It is apparent that most of the participants familiar with the building layout elected to use the normal exit route if no exit sign was noticed. Unlike those unfamiliar participants, the familiar participants were obviously not affected by the additional affordance provided by the opaque glass of the emergency exit door D2.

Among the 23 unfamiliar participants who entered A2, 9 (39%) claimed that they saw sign C1 above the emergency exit door D2. Among them, 8 (89%) made a decision to use exit door D2 rather than attempting to use the other exit, and 1 participant did not feel it was necessary to use the information provided by the sign but he still chose to use exit door D2. In addition, 3 participants claimed that they saw a sign, but could not identify where the sign was located.

Among the 20 familiar participants who entered A2, 9 (45%) claimed that they saw sign C1 above the emergency exit door D2. Among them, 6 (67%) made a decision to use exit door D2 rather than attempting to use the other door, 2 (22%) stated that their decision to use the exit was not based on seeing the sign, and 1 (11%) decided to ignore the sign and use the corridor door D1 instead. In addition, 1 participant claimed that he saw a sign, but could not identify the location of the sign.

The results can be summarised as follows, for participants who are within the VCA of an emergency exit sign measuring 0.1 × 0.3 m located above an exit and who approach the sign at a non-perpendicular angle:

- 39% (9/23) of participants unfamiliar with the building layout, 45% (9/20) of participants familiar with the building layout and 42% (18/43) of the entire sample (i.e. a population with mixed building layout familiarity) are likely to detect the sign;
- 89% (8/9) of participants unfamiliar with the building layout, 67% (6/9) of participants familiar with the building layout and 78% (14/18) of the entire sample (i.e. a population with mixed building layout familiarity) who detect the sign correctly interpret and follow the information conveyed by the sign.

Furthermore, for unfamiliar participants who did not notice sign C1 above exit door D2, the additional affordance offered by the opaque glass pane on this door greatly increased its attractiveness. However, for those participants familiar with the building, this was insufficient to encourage them to use this door to exit the building.

7.2.3.2 Exit Sign C2, Exit Selection at North Corridor A12

In total 25 participants selected the north corridor in the experiment. Among them 18 are unfamiliar participants and the other 7 are familiar participants. At the east end of A12 the participants were faced with three doors: the emergency exit door D4 with sign C2, the non-emergency exit door D5 and the locked office door D6 (see Figure 7.3b). Figure 7.5 shows how these participants made an exit selection from the available exit doors in the trials.

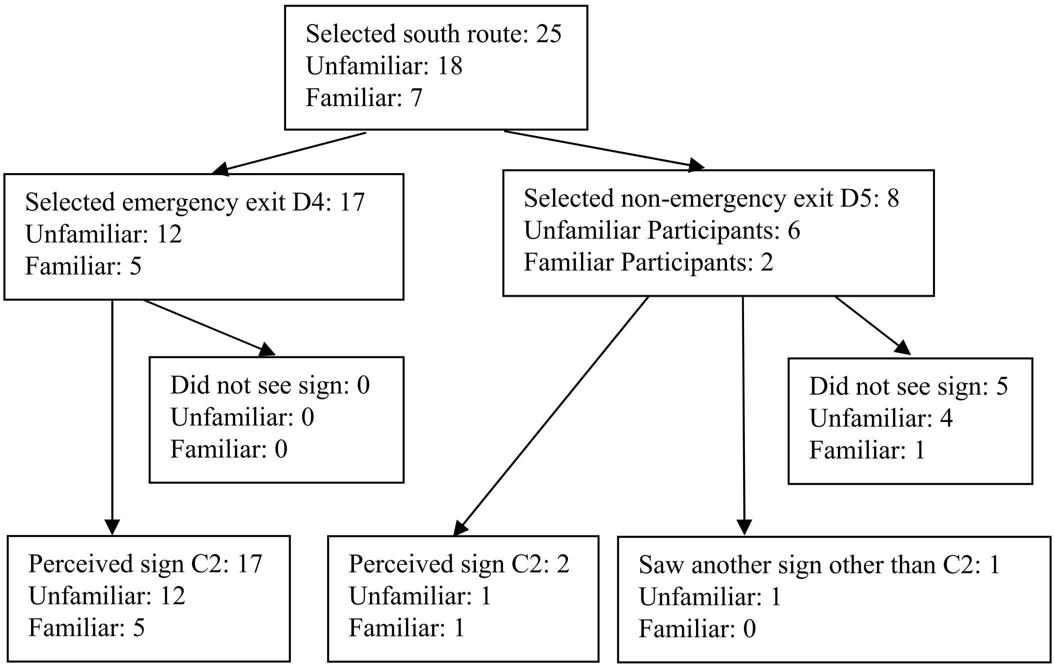


Figure 7.5: Participants' route selection at A12 on the north side of the building.

Among the 18 unfamiliar participants who entered A12, 4 (22%) failed to perceive sign C2, 13 (72.2%) claimed that they saw sign C2, and 1 claimed that he followed a sign other than sign C2. All of the 4 (100%) participants who did not see sign C2 chose to use the non-emergency exit door D5 in the path of travel. Among the 13 participants who saw sign C2, 12 (92%) chose the emergency exit door D4 and 1 (8%) chose exit door D5.

Among the 7 familiar participants who entered A12, 1 (14.3%) failed to perceive sign C2, 6 (86%) claimed that they saw sign C2. The participant who did not see sign C2 chose to use the non-emergency exit door D5 in the path of travel. Among the 6 participants who saw sign C2, 5 (83%) chose the emergency exit door D4 and 1 (17%) chose exit door D5.

The results can be summarised as follows, for participants who are within the VCA of an emergency exit sign measuring 0.1 × 0.3 m located above an exit and who approach the sign at a non-perpendicular angle:

- 72% (13/18) of participants unfamiliar with the building layout, 86% (6/7) of participants familiar with the building layout and 76% (19/25) of the entire sample (i.e. a population with mixed building layout familiarity) are likely to detect the sign.
- 92% (12/13) of participants unfamiliar with the building layout, 83% (5/6) of participants familiar with the building layout and 89% (17/19) of the entire sample (i.e.

a population with mixed building layout familiarity) who detect the sign correctly interpret and follow the sign.

7.2.4 Compare the results obtained at the three decision points

As demonstrated in the analysis in Section 7.2.1 and Section 7.2.3.1 the participants who have been categorised as 'familiar' were primarily familiar with the south route because it is more commonly used for circulation. It is also noticed that from the questionnaires that the main reason for all 7 familiar participants selecting the north route was not due to familiarity but the other influencing factors such as pre-selected route, environmental conditions and architectural configuration (see Appendix A3). In addition, 6 of them were originally categorised as 'partly familiar'. Given the above considerations, it is more likely that these 6 participants have the same level of knowledge about the north route as those unfamiliar participants. So it is appropriate to treat these 6 familiar participants equally with the other unfamiliar participants who went to the north route. The results presented in Figure 7.5 are then turned into Figure 7.6 after merging the data.

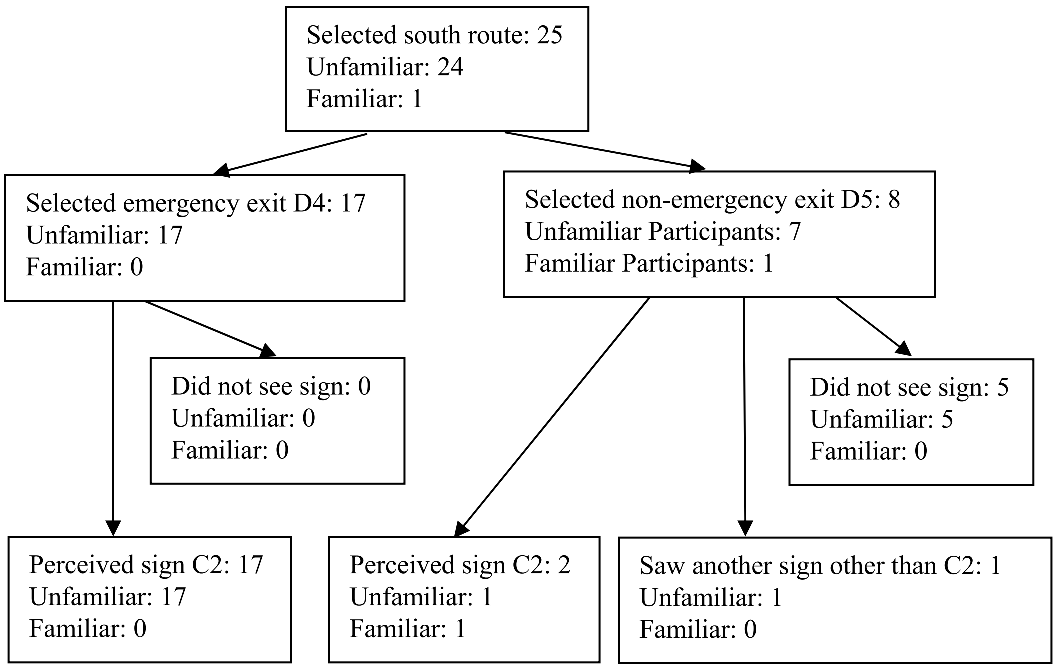


Figure 7.6: Participants' route selection at A12 after merging the data.

Although the south route and the north routes are similar in configuration (corridor dimensions, number of doors to choose from and position of exit sign) apart from the construction of two emergency exit doors in question, the results obtained on both doors are clearly different to each other (see Figure 7.7). At the south route 39% (9/23) of participants unfamiliar with the building layout are likely to detect the sign, while this percentage is 75% (18/24) at the north route. The difference between the two groups of unfamiliar participants is statistically significant ($\chi^2(1, N=47)=6.18, p=0.01$). Further examination shows that at the south route 50% (9/18) of participants who correctly selected the emergency exit door did so due to their perception of the signage above the door, while this percentage is 100% (17/17) at the north route. Thus different factors were influencing the participants at either route, and this can only be explained by the construction of the two doors, i.e. D2 at the south corridor has opaque glass pane, while D4 at the north corridor is a solid wood door. While the signage is the only source of information at the north route to the participants who had to choose between two similar wood exit door D4 and D5, the opaque glass pane on D2 acted as an additional source of information to the exit sign at the south route to the participants who had to choose between D2 and wood door D1. Thus while the sign was only detected by a small percentage (39%) of the population at the south route, a much larger proportion (78%) actually utilised the correct door. This in turn explains the low detection of the sign above the exit in the south corridor. The additional affordance provided by the natural light flooding through the glass pane reduced participants' attention to an exit sign, thereby producing the low detection rate of 39%.

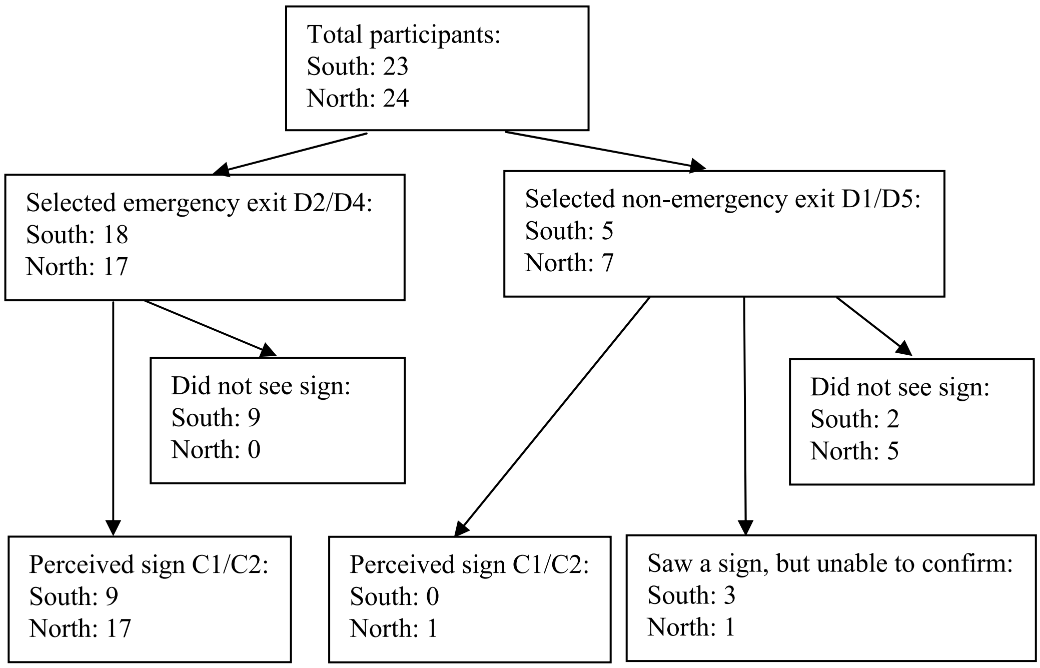


Figure 7.7: Unfamiliar participants' route selection at the south and north corridor.

The sign detection probability for the zero order sign (sign C2) above the emergency exit in the north corridor A12, i.e. 75% (18/24) for unfamiliar participants, are considerably higher than the detection probabilities for the second order sign (sign A) at the "T" intersection A7, i.e. 39% (16/41) for unfamiliar participants. This probability is also higher than the first order sign (sign B1/B2) at the corridor A6/A10, i.e. 37% (15/41) for unfamiliar participants. The differences between the detection probability of sign C2 and that of sign A and B1/B2 are statistically significant ($\chi^2(1, N=65)=7.85$, $p<0.01$; $\chi^2(1, N=65)=8.94$, $p<0.01$); while the difference between the detection probability of sign A and that of B1/B2 is not statistically significant.

Considering a comparison between the situations at the south and north route, sign C1 above the emergency exit D2 with glass pane has a lower signage detection probability (39%) than that of sign C2 (75%) above the wood exit door D4 at the north route. Besides, half of the participants selected D2 because of the appearance of the door, while all participants selected D4 mainly because they perceived exit sign C2 at the first place. It appears that D2 distracted participant's attention in the interaction with signage and effectively reduced the likelihood of the sign being perceived and used. Similarly, the differences between the higher detection probability of sign C2 and that of sign A and B1/B2 are not likely to be due to an inherent difference between zero and higher order signs (i.e. D4 is not a factor in the interaction with zero order sign C2), but are more likely due to the nature of the space that the signs are located in. The zero order sign C2 above the emergency exit D4 at the north corridor A12 is located in a confined dead-end space. At this location the participant is only faced with two wood doors and a locked office door and so must make an exit decision based on available information. In this situation, the participant is more likely to be attentive and look for an appropriate exit sign which can only be located in one of three places. This is considerably different to the situation for the second and first order signs (sign A and B1/B2) which are located in a more open space and it turns out to be relatively more difficult to identify these signs.

7.2.5 The Consistency in Successively Detecting Exit Signs

When designing signage systems for a building, it is often required that directional signs are provided at places where direct sight of an exit is not possible [BS5499-4:2000; ISO 16069:2004]. The signs should be positioned in such a manner that, if the occupants within the building follow the direction indicated by the signs successively, they should be able to reach an exit to the exterior or a place of safety eventually. Thus, the ability of successively perceiving and utilising signs is important to occupants in an evacuation. In the following section, the data is examined to test the coherence of the participants perceiving the three signs during the experiment.

A complete and continuous egress route is normally indicated by a series of signs that form a chain of indicators of direction leading to a final target. A sign in this chain can be defined as the ***successor*** of another sign if it is located closer to the final target than that sign along the route. If an observer within the VCA of a sign looking into the direction indicated by the sign can have a direct sight of a successive sign, the latter is said to be a ***direct successor***; otherwise, it is an ***indirect successor***. In general, it will be easier for occupants to follow a sign and its direct successor as they form an intuitive connection and provide consistent directional information.

In the setup of this experiment, sign B1 (B2*) is a direct successor of sign A, sign C1 and C2 are indirect successors of sign B1 and sign B2 respectively. The physical distance between exit signs A, B1/B2 and C1/C2 increases from short to long along the two routes in the following order:

1. A→B1 / A→B2,
2. B1→C1 / B2→C2,
3. A→C1 / A→C2.

Since the two routes are similar in length and signage installation, the probabilities of the participants detecting sign A and then sign B1/B2 are combined in the analysis. Also combined are the probabilities of the participants detecting sign B1/B2 and then sign C1/C2, and the probabilities of the participants detecting sign A and then sign C1/C2. All the probabilities are listed in Table 7.7.

Table 7.7: The probabilities of participants successively detecting the exit signs.

The order of encountering two exit signs	A→B1 A→B2*	B1 →C1 B2→C2	A→C1 A→C2
Relationship between the 2nd sign and the 1st sign	direct successor	indirect successor	indirect successor
The percentage of participants detecting the first sign and then its successor	67% (14/21)	59% (13/22)	57% (12/21)
The percentage of participants not detecting the first sign but detecting its successor	17% (8/47)	52% (24/46)	53% (25/47)

* Sign B2 is not in the direction indicated by sign A, but it can be seen when participant is located in the VCA of sign A.

Among the 21 participants who perceived sign A at A7 14 (67%) detected sign B1/B2 at A6/A10 too. Among the 47 participants who did not detect the sign A at A7 only 8 (17%) detected sign B1/B2. The difference is statistically significant ($\chi^2(1, N=68)=16.34$, $p<0.0001$). Thus it shows that those participants who perceived sign A are more likely to detect the direct successor sign B1/B2 than those who missed sign A.

Among the 22 who detected sign B1/B2 at A6/A10 13 (59%) also detected sign C1/C2 at A2/A12. Among the 46 participants who did not detect sign B1/B2 24 (52%) detected sign C1/C2. Among the 21 who detected sign A at A7 12 (57%) also detected sign C1/C2 at A2/A12. Among the 47 participants who did not detect sign B1/B2 25 (53%) detected sign C1/C2. It can be seen that the probability of detecting sign C1/C2 is slightly higher among those who detected sign B1/B2 or sign A. However, the differences are not statistically significant ($\chi^2(1, N=68)=0.29$, $p=0.59>0.05$; $\chi^2(1, N=68)=0.09$, $p=0.76>0.05$). Thus it shows that whether the participants detected sign A or sign B1/B2 has no significant impact on the likelihood of them detecting the indirect successor sign C1/C2.

These results confirm the importance of correctly positioning signage to form a consistent chain of wayfinding clues, as people who detect a sign tend to perceive and use a direct successor sign, while detecting a sign has no significant impact on them detecting an indirect successor sign.

7.2.6 The Influence of Signage upon Participant's Decision-Making Time

Signage in buildings can provide information to help occupants make an exit decision at places where doubt may exist about the choice of escape route or exit. If occupants successfully perceive and comprehend the information, it is expected that not only do they make a decision correctly, but they also act quickly.

Video footage from the trials was used to estimate the amount of time a participant spent in determining which direction they would travel at the "T" intersection. This was measured from the moment they entered the area to the moment they decisively headed in a particular direction, either the left or the right (see Figure 7.8). As is to be expected, the familiar participants, both those who detected the sign and those who didn't, spent less time on average in making a route selection than the unfamiliar participants (see Table 7.8). On average, the familiar participants made a route selection decision in 3.9 s while the unfamiliar participants required 4.7 s.

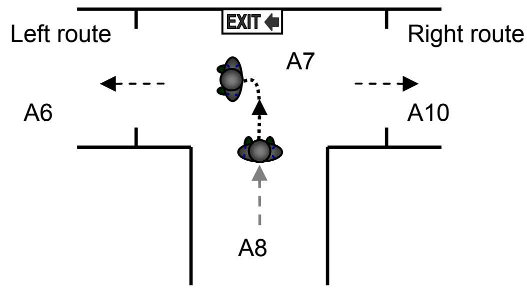


Figure 7.8: Estimate occupant decision-making time at the "T" intersection.

Table 7.8: Participant's decision-making time at the "T" intersection.

Familiarity	Detected Sign?	Number of participants	Decision time (s)			
			Minimum	Maximum	Average	STDEV
Unfamiliar	Yes	11	0.7	7.2	2.6	2.0
	No	24	2.0	9.3	5.6	2.1
Familiar	Yes	9	0.6	3.8	1.9	1.3
	No	16	1.0	11.3	5.0	2.9

Of more significance, for the unfamiliar participants, those who detected the sign had an average decision time of 2.6 s, while those who did not detect the sign had an average decision time of 5.6 s. A similar trend was observed for the familiar participants. The average decision time for the familiar participants who detected the sign was 1.9 s, while it is 5.0 s for the familiar participants who did not detect the sign (see Table 7.8). For unfamiliar participants, the decision time for those who did not detect the sign is 115% longer than that for participants who detected the sign, and for familiar participants the decision time is 163% longer. For unfamiliar participants, the difference in decision times between those who detected the sign and those who did not is statistically significant (Mann–Whitney U=229, n1=11, n2=24, P<0.001, two-tailed). A similar trend is observed for familiar participants too (Mann–Whitney U=124.5, n1=9, n2=16, P<0.01, two-tailed). However, the differences in decision times between the familiar and unfamiliar participants who detected the sign are not statistically significant (Mann–Whitney U=59.5, n1=11, n2=9, P=0.45, two-tailed), nor are the differences in decision times between the familiar and unfamiliar participants who did not detect the sign (Mann–Whitney U=232.5, n1=24, n2=16, P=0.26, two-tailed). It is apparent that the exit sign, if detected, effectively facilitates the participant's decision making process. In the test case, on average participants who did not detect the sign took more than twice as long to make a route decision as those participants who detected the sign.

Video footage recorded by the head mounted camera was used to not only measure the decision time, but also to identify different behaviours during the decision-making period. From analysis of the video footage, it is apparent that there are typically three phases in the decision-making process at the "T" intersection for unfamiliar participants who did not detect the sign. In the first phase, the participant enters the decision zone - failing to detect the emergency exit sign directly in front of them - and realises that there are two exit route options after quickly looking down both routes. In the second phase, the participant slows their walk rate and compares the two available exit routes by looking into both corridors several times. In the third phase, the participant decides on a preferred route and decisively moves off in the preferred direction. These three phases were also frequently observed for the familiar participants who did not detect the sign.

For unfamiliar participants who detected the sign, the process is a little more complex. Most participants detect the sign during Phase 1, soon after they enter the decision zone. Once the participant detects the sign, they remain focussed on the sign for a brief period to assimilate the information. Once the information conveyed by the sign is accepted (confirmed by questionnaire responses), the participant does not enter Phase 2 but goes directly to Phase 3 and adopts the signed route. It is noted that these participants do not appear to slow down appreciably during the entire decision making process. This behaviour was also noted for the familiar participants who detected the sign. However, some of the unfamiliar participants who detected the sign either have an extended Phase 1, in which they detect the sign, or enter into Phase 2 and detect the sign. This explains why a small number of unfamiliar participants who detected the sign had a long detection time (see Figure 7.9).

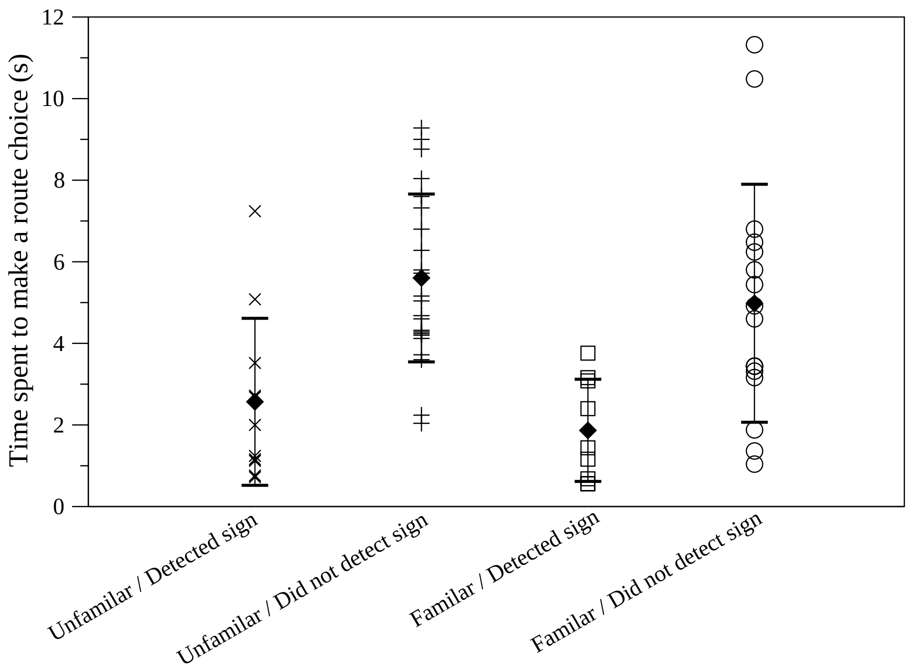


Figure 7.9: Participant's decision-making time at the "T" intersection.
(group average decision times (♦) and one standard deviation for each category are also shown)

These observations provide an explanation for the difference in average decision time between those participants who detected the sign and those who failed to detect the sign. It should be noted that this analysis is based entirely on the experimental settings and conditions. In real emergency situations, there may be additional situational cues which influence route choice, such as detecting and following others, detecting smoke or other fire effluent down a particular route etc. Nevertheless, the observations from this experiment provide some insight into how people interact with emergency signage systems.

Finally, the results from the experiment can be summarised as follows, for participants who are within the VCA of an emergency exit sign measuring 0.1 × 0.3 m and whose direction of travel makes a 0^o angle to the sign's normal (i.e. moving directly towards the sign):

- Unfamiliar participants who detect the sign require on average 2.6 s to decide which direction to take; unfamiliar participants who fail to detect the sign require on average 5.6 s to decide which direction to take;
- Familiar participants who detect the sign require on average 1.9 s to decide which direction to take; familiar participants who fail to detect the sign require on average 5.0 s to decide which direction to take.

7.3 Dataset for Modelling Occupant Interaction with Emergency Signage

The data analysis in Section 7.2 mainly focused on the specifics of the experiment, whereas evacuation modelling requires results that can be utilised in a general situation. Thus the results obtained previously need to be generalised. In this section, the data is further analysed to produce results suitable for modelling occupant interaction with emergency signage.

In the experiment a participant's interaction with emergency signage was examined at three decision points. The examination of the data-sets collected at these points shows that the participants performed similarly in the interaction with the signs at decision point 1 and 2; the perception and acceptance rates of the signs at both locations are comparable. However, these rates are clearly different from those of the sign at decision point 3. As discussed in Section 7.2.4, this difference is not likely to be due to an inherent difference between zero and higher level signs, but it is more likely due to the nature of the space where the sign is located in: the zero-level sign C1/C2 above the emergency exit at decision point 3 is located in a confined dead-end space; while the higher and first order sign A and sign B1/B2 are located in a relatively open circulation space at decision point 1 and 2. Thus the data-sets collected at decision point 1 and 2 are analysed together to produce the results for representing occupant interaction with signage in relatively open spaces and, the data-set collected at decision point 3 is analysed separately to produce the results for representing occupant interaction with signage in confined spaces.

7.3.1 Recommended Dataset for Occupant Interaction with Emergency Signage in Open Spaces

Comparing the signage interaction behaviour at decision point 1 (approaching the sign at a zero degree angle to the sign normal) with decision point 2 (approaching sign at a non-perpendicular angle to the sign normal) similar trends are found for both familiar and unfamiliar participants.

For unfamiliar participants, at decision point 1, 39% of participants detected the sign while 37% detected the sign at decision point 2. Thus both signs had a low detection rate, while the sign at decision point 2 had a slightly lower detection rate. For the sign at decision point 1, 100% of participants who detected sign A followed the sign while at decision point 2, 93% followed the sign. This indicates that if the sign is perceived almost all unfamiliar participants will correctly interpret and follow the information provided.

For familiar participants, at decision point 1, 33% of participants detected the sign while 26% detected the sign at decision point 2. Thus as with the unfamiliar participants, both signs had a very low detection rate, with the sign at decision point 2 having a lower detection rate. It is also noticed that the detection rate for unfamiliar participants is higher than that for familiar participants. This is likely due to the familiar participants feeling that they did not need to look for signage to assist them in exiting the building. For the sign at decision point 1, 100% of participants who detected the sign followed the sign while at decision point 2, 86% followed the sign. While these two percentages appear to be significantly different, the number of participants at decision point 2 who were familiar and detected the sign was quite small (seven people) and while six of the seven followed the sign, this resulted in the relatively small percentage. This again is similar to the trend found for the unfamiliar participants and it indicates that if the sign is perceived almost all familiar participants will correctly interpret and follow the information provided.

Thus the detection probability is slightly less when approaching the sign at a non-perpendicular angle compared with approaching the sign head-on for both familiar and unfamiliar participants however, this difference is not statistically significant (familiar participants: $\chi^2(1, N=54)=0.36$, $p=0.55>0.05$; unfamiliar participants: $\chi^2(1, N=82)=0.05$, $p=0.82>0.05$). The interpretation and acceptance rates are very high in both cases for both familiar and unfamiliar participants, again the differences between both signs not being statistically significant. This suggests that it is appropriate to combine both data-sets to produce a single data-set. Combining both data-sets it is found that for reflective signs measuring 0.1 × 0.3 m when observed under well lit conditions in open circulation spaces:

- 38% (31/82) of participants unfamiliar with the building layout and 30% (16/54) of participants familiar with the building layout are likely to perceive the sign;
- 97% (30/31) of participants unfamiliar with the building layout and 94% (15/16) of participants familiar with the building layout who perceive the sign correctly interpret and follow the information conveyed by the sign.

7.3.2 Recommended Dataset for Occupant Interaction with Emergency Signage in Confined Spaces

In the experiment decision point 3 was examined at two locations: the east end of the south and the north corridor. Although the two locations are similar in terms of dimensions, number of doors to choose from and position of exit sign, different trends are found for unfamiliar participants when comparing the signage interaction behaviour at both locations (see Section 7.2.4).

For unfamiliar participants, at decision point 3 in the north corridor, 75% (18/24) of participants detected the sign while 39% (9/23) of participants detected the sign in the south corridor. This difference is statistically significant ($\chi^2(1, N=47)=6.18, p=0.01$). It is verified from the questionnaires that half of the unfamiliar participants chose the emergency exit door in the south corridor because of the glass pane in the door. Although the glass is opaque it did let in a considerable amount of light so that it made the exit door more attractive (i.e. suggesting that a direct route to the exterior was available) and diverted participant’s attention to the sign. The questionnaires also confirm that all unfamiliar participants chose the corresponding emergency exit door in the north corridor because of the sign above the emergency exit door, which is made of solid wood. Given the analysis, the data-set collected at the north route is more representative than that collected at the south route concerning the interaction configuration in which unfamiliar participants approach an emergency exit sign located above an exit at a non-perpendicular angle.

It is found based on the data-set collected at the north route that for reflective signs measuring 0.1 × 0.3 m when observed under well lit conditions in confined spaces:

- 75% (18/24) of participants unfamiliar with the building layout are likely to perceive the sign;
- 94% (17/18) of participants unfamiliar with the building layout who perceive the sign correctly interpret and follow the information conveyed by the sign.

7.4 Summary

The design and installation of signage systems in buildings are often based on the supposition that occupants would detect the signs and make use of the information conveyed by the signs for wayfinding in an emergency evacuation. This is also the case in which evacuation models represent the interaction between simulated agents and signage systems. However, this only represents an ideal situation. Although the design and installation criteria ensure that the signs can be seen, there is no guarantee in reality that occupants will perceive the signs and effectively use the information. Therefore, it is essential to understand how well occupants are able to perceive the signage and how they make use of the information.

This chapter analysed the data collected by an experimental approach studying the interaction between occupants and signage systems within the built environment. The experiment was designed and conducted to determine the likelihood that individual building occupants

- involved in an evacuation situation and
- faced with a route decision point and
- located within the VCA of an emergency sign,

will perceive the sign, correctly interpret its information and correctly act upon the information.

The experimental findings suggest that the detection probability is slightly less when approaching the sign at a non-perpendicular angle (decision point 2) compared with approaching the sign head-on (decision point 1) for both familiar and unfamiliar participants however, this difference is not statistically significant. The detection rate for unfamiliar participants is higher than that for familiar participants at both decision point 1 and 2 however, this difference is not statistically significant either. While the detection probabilities found for all participants at decision point 1 and 2 are comparable, a higher detection probability is found for unfamiliar participants at decision point 3. The potential influence due to the degree of redirection information conveyed by the sign is ruled out; instead, this difference can be explained by the nature of space where the sign is positioned. The findings also suggest that most participants are likely to follow the guidance provided by signs once they are detected at all decision points. Participants who detected a sign are more likely to detect the successor of the sign than those who did not. This difference in the connected detection probabilities between these two groups of participant is statistically significant for the direct successor, but not statistically significant for the indirect successor. It is also noted in situations where the occupants approach the sign so that they are directly facing the sign (decision point 1) that on average those participants who detect the sign take less than half as long to make a route decision as those participants who did fail to detect the sign. The differences in detection times are statistically significant, irrespective of whether the participants are familiar with the building layout or not. This demonstrates that the exit sign, if detected, effectively facilitates an occupant's decision-making process. Finally, the detection and acceptance probabilities in all scenarios are listed in Table 7.9. These results provide guidance on the likely uptake of wayfinding information provided by signage.

Table 7.9: The detection and compliance rates of signs.

Type of space and sign	Degree of familiarity	Probability of detecting the sign(s)	Probability of using the signage information to assist in wayfinding
Decision Point 1/ Sign A	Unfamiliar	39% (16/41)	100% (16/16)
	Familiar	33% (9/27)	100% (9/9)
Decision Point 2/ Sign B1/B2	Unfamiliar	37% (15/41)	93% (14/15)
	Familiar	26% (7/27)	86% (6/7)
Decision Point 3/ Sign C1	Unfamiliar	39% (9/23)	89% (8/9)
	Familiar	45% (9/20)	67% (6/9)
Decision Point 3/ Sign C2	Unfamiliar	75% (18/24)	94% (17/18)
Open Spaces	Unfamiliar	38% (31/82)	97% (30/31)
	Familiar	30% (16/54)	94% (15/16)
Confined spaces	Unfamiliar	75% (18/24)	94% (17/18)

In summary, these results suggest that current emergency guidance signs are less effective in catching occupants' attention in an evacuation situation; therefore, the signs are less effective as an aid to wayfinding than they potentially can be. However, once the signs are detected, these results suggest the signs influence occupants' behaviour in the following three ways.

- The compliance rate of the signs among occupants is high, i.e. most occupants will correctly interpret the signs and follow the information.
- Occupants will be more likely to find and use the direct successor of the sign than those who did not.
- Occupants who utilised the information in the signs will spend less amount of time in making an exit decision than those who did not.

The implementation of a new signage model based on these experimental results will be described in Chapter 8.

Chapter 8
Implementation of the New Signage Model

The experimental results obtained from the two phases of experimental study on signage were introduced in Chapter 5 and Chapter 7. This chapter describes the implementation of the new signage model based on these results. The structure of the original signage model within buildingEXODUS [Galea *et al.*, 2004] is introduced at the beginning. Then the implementation of the new signage model is described. Finally, a brief comparison between the new signage model and the original signage model is given to show the difference.

8.1 The Original Signage Model

The importance of signage systems in guiding occupant's way finding in built environment has been previously addressed in evacuation modelling [Filippidis *et al.*, 2001, 2003, 2006]. Consequently, an attempt has been made to introduce a representation of the interaction between occupant and signage into the buildingEXODUS evacuation model. This approach addresses three aspects of the interaction with signage.

- *The visibility of sign*: what is the physical extent within which the occupant is able to read the sign?
- *The perception and interpretation of sign*: When the occupant is located within the area which allows the sign to be seen, how likely is it that the occupant detects the sign and correctly interprets the information conveyed by the sign?
- *The behavioural response to the information perceived*: If the occupant perceived the sign, how does the information influence their decision and subsequent behaviour?

The visibility of a sign is modelled through the manipulation of a visual catchment area (VCA) of the sign by the VCA sub-model. The perception and interpretation of the sign and occupant's behavioural response to the recognition of the sign is simulated by the interaction sub-model.

8.1.1 The Original VCA Sub-model

The VCA of a sign by definition is the area within which an occupant is able to receive the information conveyed by the sign. In reality, the physical extent of the VCA is determined by several physical and environmental factors. When calculating the VCA of a sign in the geometry, the VCA sub-model mainly takes into account the physical factors, including the height of the sign, the average height of occupants, the height of any obstacles between the occupant and the sign and more importantly, the termination boundary [Filippidis *et al*., 2003, 2006].

The VCA of a sign is represented by the VCA sub-model as a semi-circular area centred on the sign (without considering the interference of obstacles and walls). A small margin of 5 degrees is subtracted from both sides of the VCA to cater for the apparent difficulty in resolving the sign at a tangent angle (see Figure 8.1). The termination boundary of the VCA, i.e. the radius of the semi-circular, is set to be equal to the maximum viewing distance defined by relevant standards [BS 5499; the NFPA Life Safety Code Handbook]. As this definition usually represents a conservative estimation of people's ability of discerning a sign, it is reliable to adopt this maximum viewing distance to cover the eye conditions of the majority of the occupant population in the model.

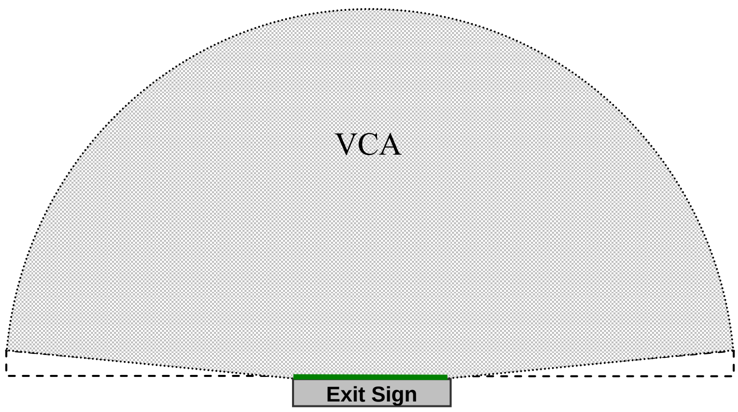


Figure 8.1: The VCA of an exit sign produced by the original VCA sub-model.

8.1.2 The Original Interaction Sub-model

Once an occupant is located within the VCA of a sign, the process of this occupant detecting, interpreting the sign and utilising the information to make an exit decision is simulated by the interaction sub-model.

In general, it is relatively easy for occupants to detect a sign positioned right in the direction of travel due to the ease of a functionary human eye seeing an object that is straight ahead. It becomes difficult to see the sign at a non-perpendicular viewing angle, i.e. the sign falls away from the occupant's head-on direction. The sign becomes invisible when it falls out of the occupant's horizontal field of view. Therefore, the likelihood of the sign being noticed will reduce accordingly as the relative orientation angle increases. The influence of the relative orientation between the occupant and the sign upon the likelihood of detecting the signs is represented in the model based on the above consideration.

The influence of the relative orientation is represented in the interaction sub-model through two independent approaches (see Section 6.2.2, Chapter 6). The first simple approach imposes an arbitrary detection probability on any agents who enter the VCA of a sign regardless of their relative orientation to the sign. In the second and more sophisticated approach, a hypothetical probability distribution is employed. This distribution simulates the increasing difficulty of detecting the sign as the relative orientation angle increases: the detection probability continuously reduces from 100% when the agent faces the sign straight ahead to zero when the agent has their back towards the sign. It should be pointed out that although the two approaches were implemented to represent the influence of the relative orientation between occupant and signage upon the detection probability, there was no real data collected that quantifies this influence.

The installation of the sign could potentially affect the interaction. A sign can be installed immediate adjacent to the target it indicates, or it can be installed at a certain distance away. An attempt was made to address this factor: a classification system has been introduced to represent the level of redirection of exit signs (see Section 6.2.1, Chapter 6). This approach however only categorised exit signs and it did not quantify the difference in the interaction between the occupant and the different installations of sign.

Apart from the influencing factors described above, the likelihood of the occupant perceiving the sign is also influenced by their attentiveness to wayfinding information. As no data was available concerning the influence of this psychological factor upon the occupant recognising and interpreting the sign, the influence was simply represented in the model by two probabilities: the recognition probability and interpretation probability [Filippidis *et al.*, 2003, 2006]. Both probabilities can be entered by the model user, while they were arbitrarily set to 100% in most cases of simulation.

After successfully recognising and interpreting an exit sign, the occupant has to decide how to act accordingly, i.e. how the sign influences the occupant's decision and behaviour. In general, the occupant can have two choices. First, the occupant adopts the target such as an exit or an exit route indicated by the sign. Second, the occupant ignores the information conveyed by the sign or the target indicated by the sign. In the first case, the target can be part of the occupant's planned exit route. Therefore, the presence of the sign would help confirm their decision and encourage them to head for the target. Alternatively, the target can be completely new to the occupant. Then the choice of the new target is the result of the occupant utilising the information conveyed by the sign and adapting their egress plan accordingly. In the second case, the occupant either decides to stick to their original plan, e.g. they are more familiar with their pre-planned route, or they have to perform other pre-evacuation tasks, e.g. looking for the other occupants prior to escaping. Therefore, they do not follow the sign in spite of perceiving the sign. In both cases, the interaction between the occupant and the sign is a process of the occupant receiving the information from the sign and making a decision.

The interaction sub-model allows an agent to manipulate exit knowledge acquired. The agent can compare a previously unknown egress route indicated by a sign with known egress routes. They will adopt a new egress route if it can reduce their evacuation time (based on a comparison of estimated travel distance) and the agent does not have other pre-evacuation tasks. However, as there was no data available concerning the probability in which the occupant will adapt their choice of egress route upon perceiving signage, the model arbitrarily assumes the probability to be 100% [Filippidis *et al*., 2003, 2006].

In addition, the visibility of a sign is also utilised in the model to determine the level of congestion around a target (usually, an exit) associated with the sign (see Section 3.3.2.2, Chapter 3). It allows the occupant to evaluate the time required to pass through a congested exit. If necessary the occupant may redirect to another farther but less congested exit to minimize the time spent waiting to pass through the exit.

In summary, the original signage model captures the physical, physiological, psychological and behavioural aspects of the interaction between occupant and signage. Using a bottom-up approach, the model initially determines the visibility of signage through the introduction of the concept of visibility catchment area to represent the physical extent within which the agent can receive information from the sign. When the agent is located within the VCA of the sign, the model then estimates the influence of peripheral vision and psychological factors upon the probabilities in which the agent detects the sign. Finally, if the agent registers seeing the sign, the model represents their behavioural response to the knowledge acquired through the introduction of adaptive exit choice behaviour. Since there was no data collected to validate each aspect of the interaction, this modelling approach mostly represents an optimal situation in which the agent will unconditionally detect and use the sign.

8.2 The New Signage Model

The original approach of modelling occupant interaction with signage is primarily based on a hypothetical analysis of the interaction, while several assumptions were also made to cater for a lack of relevant data for the time being (see Section 8.1). Therefore, despite a well established structure the original signage model is not validated as to whether the behavioural features introduced properly represent the interaction between occupants and signs in reality.

In order to address the limitations of the original signage model, a series of experimental trials have been designed and conducted (Chapter 4 and Chapter 6). The aim of the experiment is to gain an understanding of the interaction from the observational evidence and to collect the crucial data for improving the representation of signage. The development of the new signage model used the same bottom-up approach, i.e. the aspects of the interaction between occupant and signage are addressed successively to give rise to the new signage model. As each aspect of the interaction is improved based on the analysis of the data collected, the new model is able to provide a close approximation of the experimental findings.

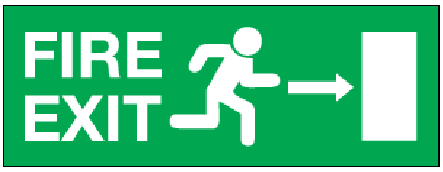
In the following sections, the implementation of the new signage model and the assumptions required in the model development are described following the coherent procedure of the interaction between an occupant and a sign. Firstly, the physical aspect of the interaction, i.e. the calculation of the VCA, is revised according to the results obtained from the first phase of the experimental trials that measured the maximum viewing distances of exit signs at various angles (Chapter 4 and Chapter 5). The implementation of the new VCA sub-model also takes into account the influence of the presence of smoke in an evacuation, making it applicable in simulating evacuation scenarios involving fire smoke (Chapter 10). Secondly, given the occupant is able to receive information from the sign, i.e. the occupant is located within the VCA of the sign, the likelihood of the occupant detecting and using the sign is represented based on the results obtained from the second phase of the experimental trials. Finally, the newly improved signage model and the original signage model are compared at the end.

8.2.1 The New VCA Sub-model

Exit signs conforming to the current legislation and standards [BS5499-4, ISO 3864-1] should consist of two components: graphical symbols and supplementary text. The supplementary text can read 'exit' or 'fire exit' which normally means an exit/fire exit door or the direction of an exit/fire exit route. As for the graphical symbols, there are two types of acceptable design subject to the regulations (see Figure 8.2). Both types of design are composed of a simple graphical representation of a running person, a door and an arrow. Both the supplementary text and the graphical symbols are necessary for the sign to achieve an acceptable comprehensibility rating among occupants.

In general, every component of the graphical symbol is larger than any individual character in the supplementary text, thus it is obviously easier for occupants to resolve the graphical symbols than the supplementary text. Therefore, when estimating the visibility distance, the maximum viewing distance required to resolve the supplementary text is considered as the threshold in the new model.

(a) BS 5499-4:2000



(b) European standard (Directive 92/58/EEC)

Figure 8.2: Two types of exit sign design.

In legislation and standards [ISO3864-1:2002, BS 5266-7:1999, BS5499-1:2002, BS5499-4:2000], the visibility of sign is often prescribed as the maximum viewing distance from which the sign has to be comprehensible. Thus by this type of definition the installation of a sign covers a semi-circular area with the radius equal to the maximum viewing distance. This method of estimating signage visibility omits the influence of the angular distortion when the sign is viewed at a non-perpendicular angle. The angular distortion effectively makes the sign hard to resolve in practice. It then requires that the viewer moves closer to the sign in order to discern the details on the sign. Therefore, this method based on a single value of maximum viewing distance overestimates the covering area of the sign.

The overestimation of the effective covering area of the sign was addressed in two ways. Firstly, a theoretical analysis of the signage visibility was conducted based on the assumption that the human eye can resolve angular separation down to a constant minimum value irrespective of observation angle. It was deduced that the VCA of the sign has a circular representation approximately at a tangent to the sign. The diameter of the circle is derived from the minimum angular separation required for the human eye to resolve the detail on the sign. The theoretical circular representation of the VCA (see Figure 8.3) apparently contradicts the original semi-circular VCA (see Figure 8.1).

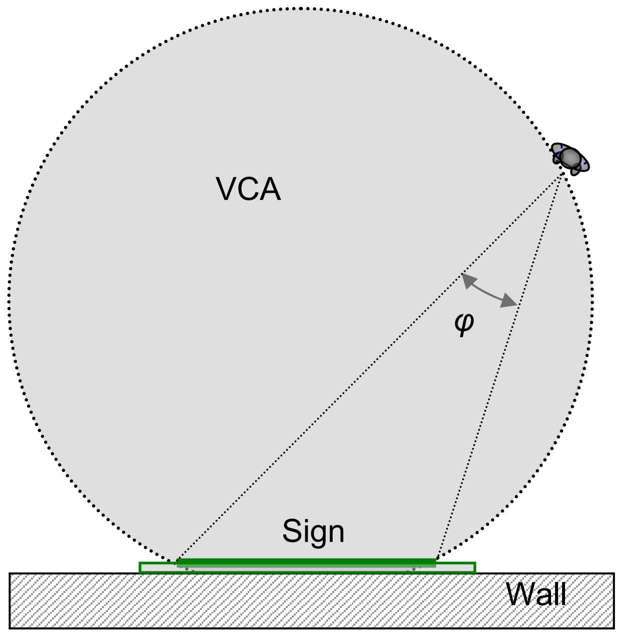


Figure 8.3: Top view of the theoretical representation of the VCA.

Secondly, the influence of the angular distortion upon signage visibility was studied through experimentation (Chapter 4). In the experiment, the maximum viewing distance of three standard exit signs at various pre-determined viewing angles were measured. The area within which each of the three signs can be resolved was obtained by connecting the average maximum viewing distances measured at these angles. The purpose of the experiment was to validate the theoretical representation of the VCA with the empirical representation. The data collected from the experiment shows that a smooth connection of the average maximum viewing distances approximates a circular area at a tangent to each sign examined. The diameter of the circle is equal to the average maximum viewing distance measured when the corresponding sign was read straight-on. The results obtained from the experiment confirm that the human eye can resolve angular separation down to a constant minimum value (φ) irrespective of the observation angle. The results further prove that the VCA of a sign has a circular representation rather than a semi-circular representation due to the angular distortion when a sign is viewed at non-perpendicular angles.

After confirming the influence of the angular distortion upon occupant resolving the detail on the sign, it is then required to set a correct value of the minimum angular separation to establish the termination boundary of the VCA. During the experiment, the maximum viewing distance of the signs when they were read straight-on was measured. The data approximates the maximum viewing distance defined in the regulations if the size of the three signs and the safety factor is taken into account. However, as only three signs were examined in a single lighting condition, the aim of the experiment was not to calibrate the relationship between the size of the sign and the maximum viewing distance, nor was the aim of the experiment to establish the minimum angular separation required to resolve the sign. Since the definition of the maximum viewing distance of sign in legislation and standards is based on extensive eye tests, and the design and installation of signage systems have to comply with the standards, it is reliable to adopt the maximum viewing distance defined in the standards to estimate the minimum angular separation required to establish the termination boundary of the VCA.

It is apparent that not all people have perfect eyesight; in fact, the visual acuity varies between individuals. When determining the value of the minimum angular separation required to resolve the signs, the condition of the eyesight of the majority of the population must be taken into consideration. A safety factor of 2 is often introduced to cater for the safety concerns [Creak, 1997], i.e. the maximum viewing distance adopted is half of the average maximum viewing distance measured for people with normal vision.

The rationale of employing the safety factor is supported by the results obtained from the experiment. For instance, the maximum viewing distance of the second sign examined is plotted as a function of observation angle in Figure 8.4. For each of the five observation angles, all the collected data points are plotted. A solid curve is plotted connecting the average maximum viewing distance measured at these angles. Also plotted is a broken curve connecting half of the average maximum viewing distance. The number of the data points falling outside the VCA outlined by the broken curve accounts for 95% of the data-set, i.e. 95% of the participants can reliably read this sign if they are located within the VCA which adopts the safety factor of 2.

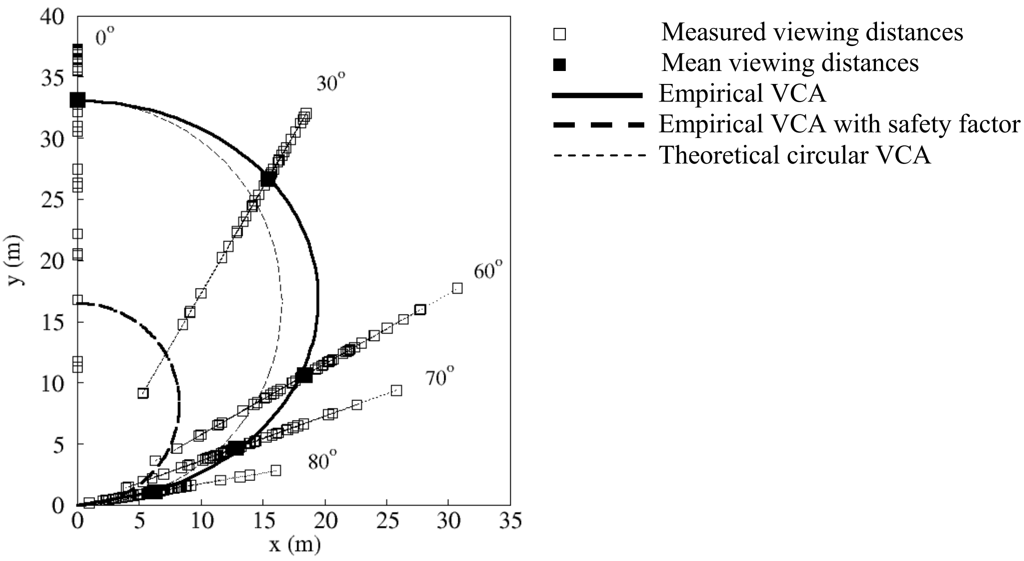


Figure 8.4: The VCA of the second sign examined in the experiment.

The new VCA sub-model takes account of the angular distortion when a sign is read at different angles and represents the area in which the sign is comprehensible as a circle. The diameter of this circle is determined by the minimum angular separation required to resolve the text on the sign. Conveniently, the diameter is set to the maximum viewing distance when the sign is viewed perpendicularly. For any signs conforming to the legislation and guideline, the maximum viewing distance is determined according to the size of sign, while a safety factor of 2 is also employed. If smoke is involved in an evacuation, the model also takes account of the visual obscuration effect of the smoke (see Chapter 10). The reduction of the viewing distance due to the presence of smoke is estimated during the simulation.

8.2.2 The New Interaction Sub-model

When an agent enters the VCA of a sign determined by the VCA sub-model, the interaction sub-model is employed to determine whether the agent perceives the sign and follows the information conveyed by the sign. This is conducted in two steps. First, the influence of the relative orientation between the agent and the sign upon the likelihood of detecting the sign is estimated. Second, the process of the agent perceiving the sign and utilising the information conveyed by sign is simulated.

8.2.2.1 The Relative Orientation between Occupant and Signage

An object is ready to be seen only when it falls into the viewer's field of vision. Thus, whether an occupant is able to see a sign is not only determined by the maximum viewing distance of the sign (represented by the VCA), but also the human field of vision and the relative orientation between the occupant and the sign.

The human field of vision is determined by the vertical field of view and the horizontal field of view. As a sign is most likely to be within the vertical field of view (Section 6.2.2, Chapter 6), here the impact of the horizontal field of view is discussed. People with normal eyesight can have a 200° forward-facing horizontal field of view [Werner, 1991]. This field of view includes a central binocular (seen by both eyes) field of vision and two peripheral monocular (seen by one eye) fields of vision [Henson, 1993] (see Figure 8.5). If the viewer moves head and eyes around, the field of view can be extended to a larger angle. However, despite the vast range of horizontal fields of view, there are two restrictions preventing an immediate recognising of the sign within the field of view. Firstly, human eyes have a narrow cone of 2 degrees with high visual acuity in the middle. The occupant has to move their eyes and focus on the sign within the binocular field of vision to be able to read the information. Considering the nature of the human eye and the way in which the information is perceived, a sign falling into the peripheral view has less chance to be noticed than a sign in front. Secondly, when the occupant is on the move, they may not move their head and eyes around very often, but rather paying more attention to the situation in the direction of travel. Therefore, the likelihood of the occupant detecting the sign is related to the relative orientation between them; the sign is more likely to be seen if it is close to the occupant's direction of travel or the direction in which the occupant is facing.

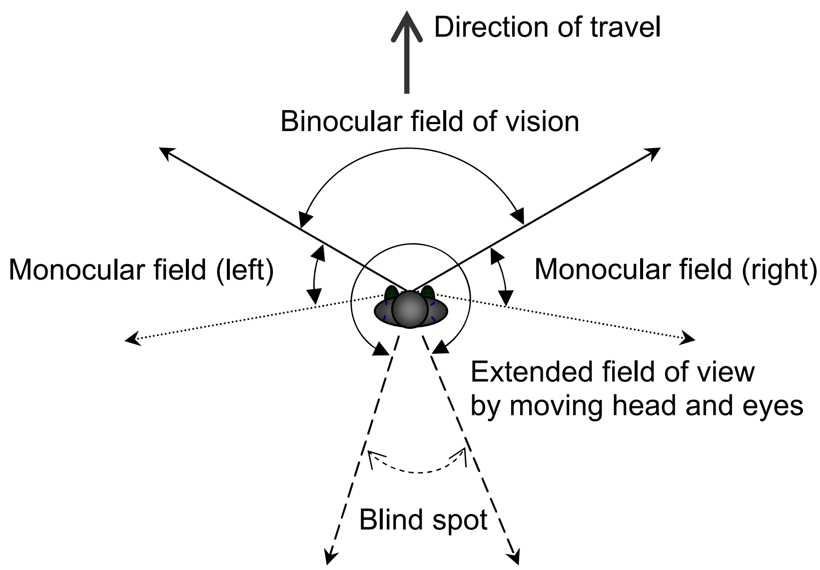


Figure 8.5: The horizontal field of view.

Ideally, the model should represent each occupant's field of vision and determine whether a sign falling in their field of vision can be perceived, taking into account the relative orientation between the occupant and the sign. As no published data is available regarding the relationship between the relative orientation and the detection probability, the previous interaction sub-model represented the influence of the relative orientation upon the detection probability through two methods (see Section 8.1.2). In the first method an arbitrary probability is applied for any agent entering the VCA of a sign irrespective of the orientation angle. In the second method, a hypothetical distribution is used to represent the probability of detection as a function of the orientation angle. Both methods represent an attempt to represent the impact of the relative orientation upon the likelihood of perceiving a sign in the model. However, it can be seen that the second method is better than the first method in matching the analysis of the relationship between the human field of vision and the probability of detecting the sign. As there is still a lack of relevant data, the new interaction sub-model inherits the second method for the time being (see Figure 6.6, Chapter 6).

In buildingEXODUS, a sign can be placed relatively free at any location in a geometry and face any desired direction. However, an agent who occupies a node (non-boundary) can only face one of the eight directions and travel along the corresponding arc connection (see Figure 8.6). As the relative orientation between the agent and the sign is determined by the position of the sign in relation to the direction in which the agent is facing or travelling, the model effectively restricts the accuracy of representing the impact of the relative orientation on the probability of detecting the sign.

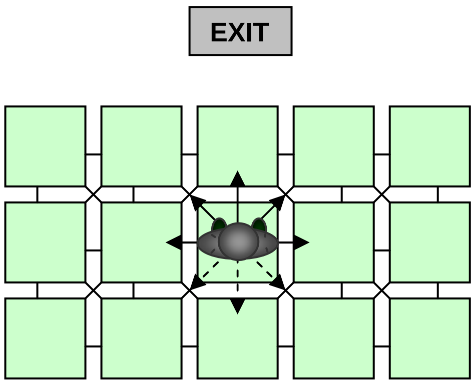


Figure 8.6: An example of eight directions in which an agent can face and travel.

8.2.2.2 Influencing Factors in the Interaction between Occupant and Signage

There are several factors which may influence the process of an occupant perceiving, interpreting and utilising signage during an evacuation (Chapter 6). The main factors identified during the design phase of the experimental study on the interaction include

- the occupant's degree of familiarity with the building layout,
- the method in which the occupant approaches the sign,
- and the level of directional information conveyed by the sign.

Each of the factors has either 2 or 3 variables, so that the combination of these variables produces multiple scenarios of an occupant encountering and interacting with signage. These scenarios have been examined through experimentation: participants interacted with the signs at three decision points respectively in a built environment; data was collected to estimate the impact of these factors on the likelihood of occupant perceiving and utilising the signs (Chapter 7). Their interaction with the signs is recognised by the actions of individual participants detecting one or more signs and utilising the information perceived to make an exit decision during the experiment. The effectiveness of each sign examined is represented by the detection rate and compliance rate of that sign. The experimental results show that the three signs have different detection rates while their compliance rates are similar and relatively high. This suggests that the signs have different attractiveness to catch a participant's attention, but once the signs were detected most of the participants interpreted and used them in a similar manner. Therefore, it is appropriate to focus on the detection rate to analyse the effectiveness of each sign.

In this section how the experimental results are utilised to represent the interaction between occupant and exit sign is described. The three factors (numbered F1-F3) identified are reviewed to begin with. The implementation of the new interaction model is described at the end.

F1. Familiarity

The difference in the signage interaction behaviour between familiar participants and unfamiliar participants is examined at the three decision points. The experimental results show that while all the other conditions remain the same, the detection probabilities of unfamiliar participants found at decision point 1 and 2 are slightly higher than those for familiar participants. However, the differences are minor and not statistically significant (Section 7.2.1 and Section 7.2.2, Chapter 7). The situations at decision point 3 in the south corridor and the north corridor are different. In the south corridor (Section 7.2.3.1, Chapter 7), the results show that nearly half of the familiar participant chose the exit door without a sign because they were familiar with it, while the other half chose the exit door indicated by the sign mostly because they noticed the sign. The majority of the unfamiliar participants chose the door indicated by the sign: half of them did so because they perceived the sign, while the other half did so because they were attracted by the appearance of the door (light coming through the glass pane). In the north corridor (Section 7.2.3.2 and Section 7.2.4) the results show that the majority of the unfamiliar participants chose the exit door indicated by the sign, and all of them did so because they perceived the sign. However, there are not enough familiar participants; hence a comparison is not possible. It should be pointed out that the situation in the north corridor is more representative than the south corridor where the glass pane is an extraordinary influencing factor.

Considering the above analysis and that the unfamiliar participant population is larger than the familiar participant population, the following analysis focuses on the unfamiliar participant population unless otherwise stated.

F2. Relative orientation and method of approaching sign

The relative orientation between the occupant and the sign has two forms of impact on the interaction. The first form, from a static point of view, concerns the difficulty in discerning the sign in an off-centre direction at each step. This impact has been addressed in Section 8.2.2.1. A detection probability as a function of the relative orientation angle is introduced to represent the difficulty in detecting a sign located at an angle to the occupant's direction of travel.

The second form, from a dynamic point of view, concerns the influence of the relative orientation between the occupant and the sign during the process in which the occupant approaches the sign. The relative orientation angle is determined by both their positions and the directions in which they are facing. Since it is difficult to explicitly measure this angle at every step of approaching the sign, it is impractical to examine the influence of this angle through experimentation. However, considering the usual position of a sign in a built environment and the occupant's direction of travel along an egress route, the methods of approaching the sign can be generalised into two common forms. In the first method, the sign is positioned in the occupant's direction of travel. For instance, a sign is suspended in the middle of a path. When the occupant approaches this sign, the relative orientation remains unchanged. In the second method, the sign is positioned by the side along the occupant's direction of travel. For instance, a sign is positioned on the wall of a path. When the occupant approaches this sign, the relative orientation keeps changing. Therefore, the design of the experiment did not examine the influence of the relative orientation between the occupant and the sign according to the relative angle, but the two methods in which the occupant approaches the sign (Section 6.2.2, Chapter 6).

The influence of the two methods of approaching the sign upon the signage interaction behaviour is compared at decision point 1 (approaching the sign at a zero degree angle to the sign normal) and decision point 2 (approaching sign at an angle to the sign normal). Similar trends are found for both familiar and unfamiliar participants: the detection rate of the sign at decision point 1 is slightly higher than that of the sign at decision point 2. However, the differences are minor and not statistically significant (Section 7.2.4, Chapter 7).

F3. Level of directional information conveyed by the sign

In the original signage model, exit signs are categorised into 3 levels: zero, first and higher level according to the directional information conveyed and the relationship between the sign and the target it indicates [Filippidis *et al.*, 2006]. A zero-level sign is normally positioned immediately adjacent to the target it indicates. A first level sign is normally positioned a certain distance to its target, while it maintains direct visual access to this target. Similar to the first-level sign, a higher-level sign is also positioned a certain distance to its target, but at locations where it is not possible to have direct visual access to an immediate exit. As representing a zero-level and first-level sign is relatively more straightforward than representing a higher level sign, currently the model only considers the first two levels of sign and leaves the modelling of the higher-level sign to the future work.

The influence of the level of redirection information conveyed by the sign was examined through participants' interactions with the signs which represent the higher-level, first-level and zero-level signs respectively at three successive decision points. Firstly, the difference between the detection rate of the higher-level sign and that of the first-level sign is minor and not statistically significant. This is consistent with the fact that these two types of signs are similar in that the signs and targets associated are not in close vicinity. Secondly, the zero-level sign at the south corridor has a lower detection rate than the same zero-level sign at the north corridor, and the difference is statistically significant. This is explained by the difference in the construction of the two exit doors indicated by the two signs respectively. Half of the participants selected the door in the south corridor because it has a glass pane which allows light coming through, while all of the participants selected the solid wood door in the north corridor mainly because they saw the exit sign above the door. This result suggests that if the target indicated by a zero-level sign is attractive, it effectively reduces the likelihood of the sign being noticed. It should be noticed that the circumstance in the north corridor is more representative than in the south corridor in buildings. Thirdly, the detection rates of the higher level and first level sign are lower than that of the zero-level sign in the north corridor, and the difference is statistically significant. Given the wood exit door in effect is not attractive and directly involved in the interaction, the higher detection rate found in the north corridor sign can not be explained by the difference between a zero-level sign and first/higher level sign.

In addition, it is noticed that the compliance rates of all three levels of signs are comparable with no significant difference. This suggests that once the participants perceive the signs, they uptake and utilise all three levels of signs in a consistent manner. Since the difference in the level of redirection information conveyed by exit signs mostly makes sense during the process of occupants interpreting the signs, it is unlikely that the variation in the detection rate is caused by the levels of directional information conveyed by these signs (with the exception of the unusual circumstance in the south corridor).

F4: Additional factor: the nature of the space

In the analysis of the F3 factor, it is noticed that the difference in the detection rate between the level-zero sign and the first/higher-level sign can not be explained by the listed factors. According to the analysis in Section 7.2.4 in Chapter 7, it was found that the nature of the spaces where the signs are positioned is different. The zero-level sign in the north corridor is positioned in a confined dead end space, while the first-level and higher-level signs are positioned in a more open circulation space. Comparing the situations at these two locations, it is clear that it is more difficult for the participants to detect a sign of the same size in an open space than in a confined space, because more time and effort is required to scan a larger space to spot a sign. Therefore, the difference in the detection rates between the signs is more likely to be due to the nature of the space where these signs are positioned. This factor is further discussed in Section 8.2.2.3.

8.2.2.3 The Detection Probability and the Compliance Probability

The review (Section 8.2.2.2) of the experimental results shows that there is no significant difference between unfamiliar and familiar participants at decision point 1 and 2. However, the comparison is complex at decision point 3. As only a small data-set was available, it is difficult to draw firm conclusions. Besides, there is an unusual factor (glass door) in the south corridor involved in the interaction. For this reason, data from decision point 3 at the south corridor is not included in the modelling. Considering the similarity in the signage interaction behaviour between unfamiliar and familiar participants at decision point 1 and 2, and that the unfamiliar participant population is larger than the familiar participant population, the new interaction sub-model will be based on the data collected for unfamiliar participants and does not explicitly distinguish unfamiliar and familiar participant.

The review also shows that the variables of the other two factors, i.e. the method of approaching a sign and the level of redirection information conveyed by the sign, do not produce significant differences in the detection rate. However, the nature of the space where the signs are positioned is identified as an influencing factor in the interaction with signage. The detection rate of the sign positioned in a confined space is higher than that of the sign positioned in an open space, and the difference is significant. Thus, the new interaction sub-model takes this influencing factor into account and replaces the idealised 100% probabilities of detection and acceptance in the original interaction sub-model with the experimental data.

The nature of the space in which the sign is located is examined to determine the detection and compliance rates of that sign. Effectively, the model estimates whether the sign is located in an open space or it is located in a confined space. This is estimated by comparing the actual VCA of the sign with the maximum possible VCA of the same sign. If the sign is located in a relatively confined space, the ratio will be a relatively small value; the ratio will be a large value (up to 1) if the sign is located in an open space. The relationship between the ratio of VCA coverage and the detection rate is determined according to the experimental results.

Five standard escape route signs of the same size were used in the experiment. The estimated maximum viewing distance of these signs is 13 m [BS5499-4:2000] taking account of both the height of the graphical symbol on the signs (75 mm) and the vertical illuminance at the sign surface (100~200 lux). The layout of the test area where the trials were conducted is recreated in buildingEXODUS (see Figure 8.7). Table 8.1 lists the VCA coverage of the five signs calculated by the software.

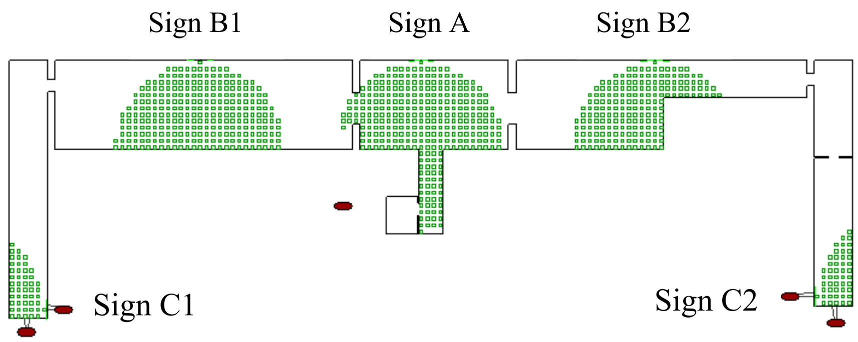


Figure 8.7: The VCAs of the five signs in the test area.

Table 8.1: The VCA coverage of the five signs.

Sign	Location	Maximum possible VCA area (m^2)	Actual VCA area (m^2)	VCA coverage ratio
A	A7	132.25	78.50	59%
B1	A6	132.25	69.00	52%
B2	A10	132.25	47.50	36%
C1	A2	132.25	12.00	9%
C2	A12	132.25	12.00	9%

Sign A, B1 positioned in a similar open space in the horizontal corridor have the same level of VCA coverage of over 50%. Sign B2 is positioned in the same corridor. However, the VCA coverage of sign B2 is reduced to 36% due to a lecture room occupying the bottom right corner of the corridor. Considering that participants approach sign B2 from the left open side of the corridor, the lecture room does not restrict participant's view until they pass the sign. The experimental results obtained from the experiment also confirm that the difference in the detection rates of the three signs is not statistically significant (Section 7.2.4, Chapter 7). Thus, it is appropriate to equally treat the situation of sign B2 with that of sign A and B1. The spaces in which sign C1 and C2 are positioned is significantly different from those of the other three signs. These two signs positioned in a confined space have a small and identical VCA coverage of 9%.

The relationship between the detection probability and the VCA coverage of a sign obtained is extrapolated to produce a full description of the relationship (see Figure 8.8). This is based on the assumption that (1) when the VCA coverage is lower than 9% or higher than 52% the detection probability remains the same value as the detection rates obtained from examining the signs at relatively confined and open spaces respectively in the experiment; and (2) when the VCA coverage is between 9% and 52%, the detection probability is obtained through linear interpolation.

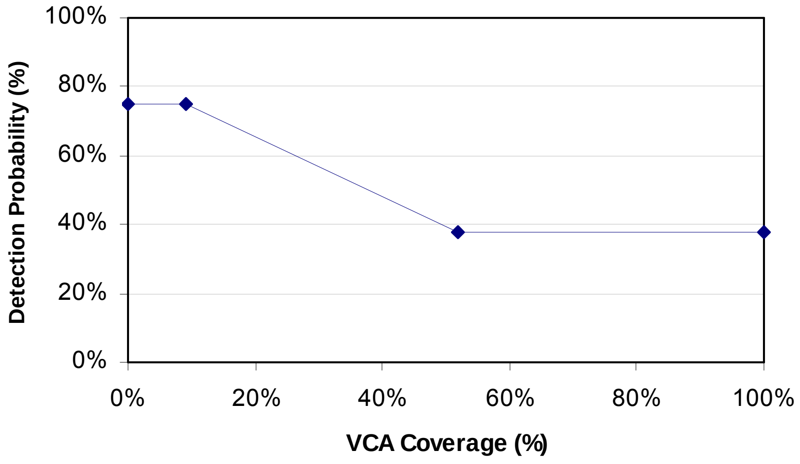


Figure 8.8: The relationship between the detection probability and the VCA coverage.

Since no significant difference is found for compliance rate for all signs, the compliance probability adopts the average value, i.e. 96%.

8.2.2.4 Modelling Occupant Interaction with Signage

The process of occupant interaction with signage is illustrated in Figure 8.9. Initially the agent approaches the sign and enters the VCA of the sign at time T_0. The agent continues to travel across the VCA along the original direction of travel. If the sign is not detected or the information is not accepted (either not interpreted or not to comply with), the agent will exit the VCA at time T_2. During the period between T_0 and T_2, the overall likelihood of this agent detecting the sign is P_d, assuming that the relative orientation between the agent and the sign allows the sign to be seen (see Section 8.2.2.1). Once the sign is detected, depicted as time T_1 in the figure, the likelihood of the occupant accepting the information on the sign is P_a. Note that P_d and P_a are determined by the formula described in Section 8.2.2.3.

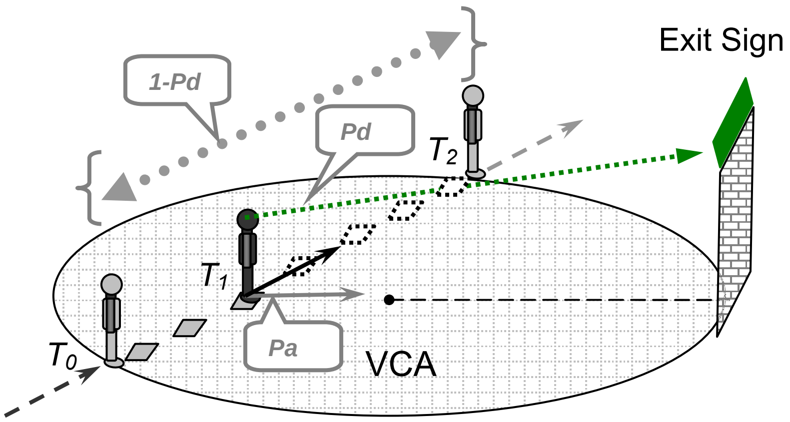


Figure 8.9: Agent detecting exit sign while within the VCA of the sign.

Whether the agent detects the sign is successively assessed while the agent is travelling across the VCA. The probability of the agent detecting the sign at each step is denoted as P_s. Assuming P_s is equal at each step, then the accumulated probability in which the agent fails to spot the sign is $(1-P_s)^N$, where N is the total number of steps the agent expects to make in crossing the VCA (N=7 in the example shown in Figure 8.9). The relationship between P_d and P_s is determined by

$$P_d = 1-(1-P_s)^N \,, \qquad \textbf{(Equation 8.1)}$$

or

$$P_s = 1-(1-P_d)^{1/N} \,. \qquad \textbf{(Equation 8.2)}$$

If the agent detects the sign at time T_1, the likelihood that the agent will accept the information conveyed by the sign and the consequent decision making process are assessed. Within the model, there are two possible actions the agent can take: either the agent follows the information conveyed by the sign or they do not follow it. When the agent detects the sign, the knowledge of the new exit indicated by the sign is added to the agent's exit awareness.

The agent then estimates the time required to reach the indicated exit and compares it with the time required to reach the original target exit (the estimation is based on travel distance and maximum travel speed). If the estimated time to the indicated exit is shorter, the acceptance probability P_a is applied to determine whether the agent should redirect to the indicated exit or continue on their originally planned journey. If the estimated time to the indicated exit is longer, the agent ignores the indicated exit and continues their journey as originally planned. It should be noticed that this decision-making process is based on an assumption that occupants can use the directional information conveyed by signage systems to find the shortest escape route leading to a place of safety or a final exit. This assumption is consistent with the principle of designing signage systems [BS5499-4:2000], which requires the signs to indicate the shortest travel distance.

8.2.3 The Requirement of Implementing the New Signage Model in Other Models

The development of the new signage model is not restricted to buildingEXODUS, i.e. the model can be presented and applied elsewhere. The implementation of the algorithm is dependent on the method adopted by other models to represent the geometry. For the three method described in Section 2.4.1, Chapter 2, the elements would need to be present in the other models for the algorithm to be employed are now suggested.

1. Coarse network model

It is suggested to define a node that is corresponding to the size and location of the VCA of a sign. Then the detection and compliance probabilities can be assigned to this node. They will be utilised to determine whether agents passing through the node will perceive and use the sign associated with the node.

2. Fine network model

The implementation will be the same as the present model implemented within buildingEXODUS.

3. Continuous model

It will be largely the same as the fine network models if the models use a fine node network to map a building geometry. If not, the model needs to define an area using their means to represent the VCA. Besides, the model needs to assign detection and compliance probabilities according to their simulation clock when agents are travelling through the VCA of a sign.

In general, the elements need to be present are the ability to define an area and a measure of the span in which an agent is travelling across this area.

8.3 Summary

This chapter described the implementation of the new signage model. The model is composed of two sub-models: the VCA sub-model and the interaction sub-model. The VCA sub-model represents the physical area (i.e. the VCA of a sign) within which an agent is able to receive information from the sign in the signage model. The interaction sub-model determines whether an agent located within the VCA of a sign perceives the sign or they do not. It also determines how the agent makes use of the information conveyed by the sign if they perceive the sign. The development of the two sub-models is based on the data collected from the two phases of experimental studies of the interaction with signage.

The VCA sub-model takes account of the influence of the angular distortion and the maximum viewing distance that is appropriate for the majority of people. Due to the angular distortion, the VCA of a sign has a circular representation rather than a semicircle represented by the original signage model. This circular representation has been verified both theoretically and experimentally. When determining the termination boundary of the VCA, the VCA sub-model applies a safety factor to the maximum viewing distance of the sign. This method produces a conservative estimation of the VCA which covers the eye conditions of the majority of the population. The new method of calculating the VCA provides a more accurate and reliable estimation of the visibility limits of the sign than the original signage model.

The representation of the signage interaction behaviour in the original signage model was based on an analysis of the factors, which potentially influence occupant detecting and utilising the sign during an evacuation. The model executes a series of evaluations to determine whether the agent sees the sign and correctly interprets the information on the sign when they are located within the VCA of the sign. These evaluations include

1. Considering the relative orientation between them, is the agent able to detect the sign?
2. Does the agent recognise the sign if they are able to detect the sign?
3. Does the agent correctly interpret the information on the sign if they recognise the sign?

The impact of the factors involved in the evaluations is assessed successively, while the probability associated with each factor is applied. Whether the next evaluation will be conducted or it will be discarded depends on the result of the previous evaluation, i.e. the next evaluation will be conducted if the previous evaluation confirms a successful “communication” between the agent and the sign. Since there was no detailed data available addressing the influence of these factors at the time of model development, the original signage model used the ideal values (a 100% detection rate and a 100% interpretation and compliance rate) to represent the interaction in simulations.

The original signage model treats the physical and psychological factors independently. However, it is more likely that the interaction between occupant and signage is influenced by these factors acting simultaneously. Thus, it is impractical to estimate the influence of these factors independently from the observational evidence. For instance, if an occupant failed to perceive an exit sign once appearing in their field of view during an evacuation, it is almost impossible to explicitly determine whether they did not focus on the sign or they did not pay attention to the information. Therefore, this approach faces a difficulty in collecting the necessary data required by the model.

The new interaction sub-model adopts a different and more programmatic approach in representing the interaction between occupant and signage. The new modelling approach determines the likelihood of the agent perceiving and utilising the sign according to the interaction configuration in which the agent encounters the sign. Each occurrence of the interaction is identified by the determinate variables of the control factors involved, such as the agent's level of familiarity with building layout, the method of approaching the sign, the level of redirection information and the nature of the space where the sign is positioned (note that only the variables of the last factor are confirmed to make a significant difference in the interaction). The impact of these factors and the other indeterminable psychological factors upon the agent perceiving and utilising the sign is represented by the detection and compliance probabilities obtained in the experimental studies. The appropriateness of the new model is dependent on the data collected from the experiment that simulated the interaction with signage.

Chapter 9
The Demonstration Cases

9.1 Introduction

In this chapter, the application of the new signage model described in Chapter 8 in evacuation simulation is demonstrated through two hypothetical evacuation cases in two public buildings: a large-scale building with a simple structure and a small, but relatively complex building. The purpose of implementing these two demonstration cases is to show how evacuation models can utilise the signage model to examine the impact of emergency exit signs upon occupant's exit route/exit door selection, and assess the effectiveness of the emergency signage systems in assisting occupants during an evacuation. This is achieved by comparing the results of running evacuation simulations in the following situations:

1. with no representation of the interaction between occupants and signage, but allow them to use the main exits and all exits respectively,
2. with representation of the interaction in an ideal situation (representing the capability of the original signage model in buildingEXODUS, see Chapter 3),
3. and with a representation of the interaction based on the empirical results (representing the capability of the new signage model, see Chapter 8).

9.2 Case One

There is a tendency in public building design to increase the scale of buildings. Supermarkets, for example, often have a very large span to cater for the increasing demand for storage and shopping spaces. There are two reasons for such a built environment to provide wayfinding information to occupants. Firstly, although large-scale buildings can have a simple structure, it may not be easy for occupants to locate the exits due to complex interior configuration. Secondly, large-scale enclosures usually have egress capacity provided by exits only used in emergencies. Occupants may not be aware of these additional means of escape. Therefore, occupants within a large-scale building require assistance to quickly identify viable routes leading to the exterior or a place of safety if an evacuation is required. The installation of exit signs, which are not necessarily positioned adjacent to target exits, can cover the area from where it is not possible to see these exits, and effectively reduce the difficulty of finding an appropriate egress path.

9.2.1 Definition of Geometry and Test Population

The first demonstration case is based on a hypothetical single-floor supermarket. The geometry of the supermarket approximates a rectangular area of 79 m in width and 55 m in depth (see Figure 9.1). There are eight exits around the supermarket in total. Of these, the four located at the front (south) are used for normal circulation: the one on the right (Exit 6) is the main entrance of the supermarket; the one on the far left (Exit 3) is the main exit of the supermarket; the other two in the middle (Exit 4 and 5) are open to a café area. The majority of the patrons are familiar with these four exit doors as they are mostly used during normal circulation. The other four exits (Exit 1, 2, 7 and 8) located on the east and west side of the supermarket are emergency exits which are only used in emergencies. All exit doors are 2.5 m in width except the main entrance, which is 2 m wide.

The interior of the geometry is equipped with supermarket shelving, tills and tables. The majority of the shelving is at a height of 2.5 m. However, there are some with a height of 1.8 m, and the tills and tables in the café area have a height of 1.2 m. The total available area where the simulated agents can manoeuvre within the geometry has been calculated to be approximately 2927 m^2 after the shelving and the other furnishings have been taken into account.

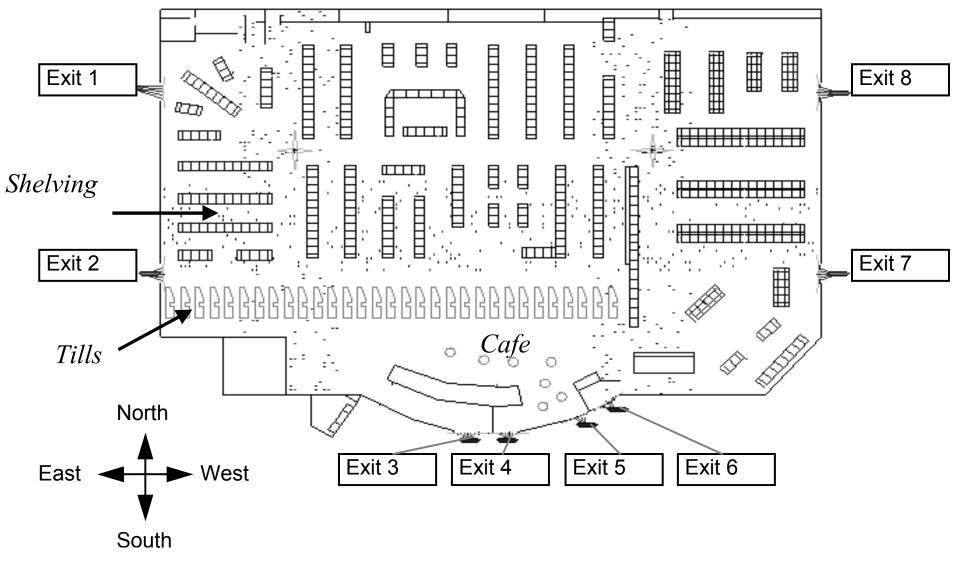


Figure 9.1: The geometry of the hypothetical supermarket.

A total of 1000 agents are used in the demonstration simulations to represent a general population of patrons. They are randomly generated using the standard buildingEXODUS default options (travel speeds ranging from 1.2 m/s to 1.5 m/s) [Galea *et al.*, 2004] and located throughout the geometry. For the purpose of these demonstrations it is assumed that the agent population is fully mobile (no movement disabilities) and they react instantly to an evacuation alarm. It is also assumed that the entire population is unfamiliar with the geometry (except in Scenario 2 described below) and so only know of the main entrance/exit to the supermarket. The average agent height is assumed to be 1.75 m when calculating the coverage area of the VCAs of the exit signs.

9.2.2 Simulation Scenarios

Four scenarios are examined. Scenario 1 and 2 are two base cases with no representation of the interaction between the agents and the signage system, while the interaction is enabled in Scenario 3 and 4. Scenario 1 and 2 are used to compare with Scenario 3 and 4.

The details of Scenario 1 and 2 are now described.

Scenario 1: The entire population utilise the four main exits (Exit 3, 4, 5 and 6) only. All signage information is ignored; hence no emergency exits are used. This is intended to represent a base case situation which is a plausible worst egress scenario as the additional egress capacity provided by the emergency exits is not utilised.

Scenario 2: The entire population utilise every available exit, while all signage information is ignored too. The agents' choice of exit is simply based on an estimation of the distance to all available exits, and they will try to use the nearest exit leading to the outside. This is intended to represent a best case situation or an optimal case in which every agent has complete knowledge of the layout of the building. The likely results of a real evacuation are expected to fall between the results of Scenario 1 and Scenario 2.

Both Scenario 1 and 2 are the type of scenario that most current egress models are capable of simulating, while Scenario 3 and 4 require the capability of representing the interaction between occupants and signage system. This capability is currently lacking in most egress models. Even those that include a representation of a signage system are not based on empirical data; therefore, it is only provided as a simple feature based on untested assumptions (see Section 2.4.2.2, Chapter 2).

Two sets of exit signs are included in Scenario 3 and 4. All exit signs are placed at a height of 2.2 m above the floor. The lettering on each sign is assumed to be 15.2 cm in height producing a maximum visibility distance of 30 m [the NFPA Life Safety Code]. The VCA of each sign is circular in shape as determined in Section 8.2.1, Chapter 8.

The first set consists of eight exit signs positioned directly above each of the main and emergency exits, one sign above each exit. The VCAs of the four exit signs indicating the location of the four emergency exits covers 947.3 m^2 of floor space and so an emergency exit can be seen from 32.4 % of the floor space. The VCAs of all eight exit sign cover 1389.8 m^2 of floor space and so a main exit or an emergency exit can be seen from 47.5% of the floor space (see Figure 9.2). The blank space left in the geometry between some shelving units represents the area from which it is not possible to see any sign or exit.

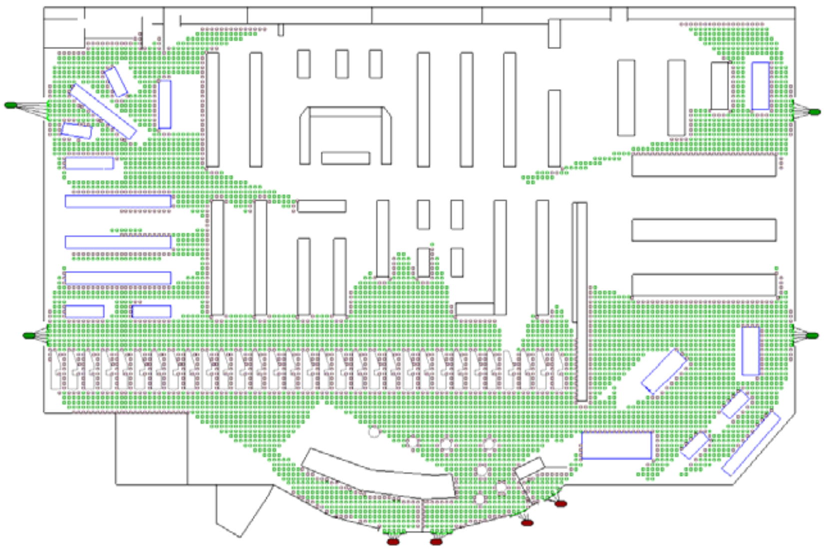


Figure 9.2: The VCA coverage of eight exit signs above the main and emergency exits.

A second set of signs is added to cover the blind area. This set of signs consists of two groups of four exit signs positioned above the main central aisle that runs from east to west across the geometry. One group is located to the left and the other group is located to the right of the centre aisle (see Figure 9.3). These eight signs indicate the location of the four emergency exits on the east and west side of the supermarket. The VCA of these eight exit signs covers 1474.23 m^2 of floor space and so these emergency exits can be seen from 50.4% of the floor space. These eight exit signs cover 18% more area than the four exit signs positioned above the four emergency exits.

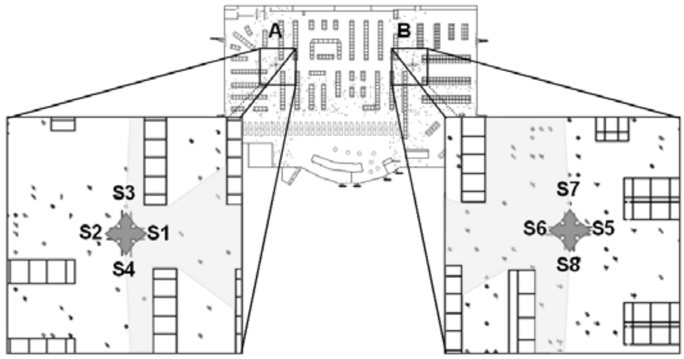


Figure 9.3: The eight exit signs located within the geometry above the main central aisle.

The two sets of all 16 signs covers 1914.5 m^2 of floor space in total and so an emergency exit or a main exit can literally be seen from 65.4% of the floor space (see Figure 9.4). It is expected that the additional eight signs positioned above the main central aisle will increase the overall effectiveness of the signage system.

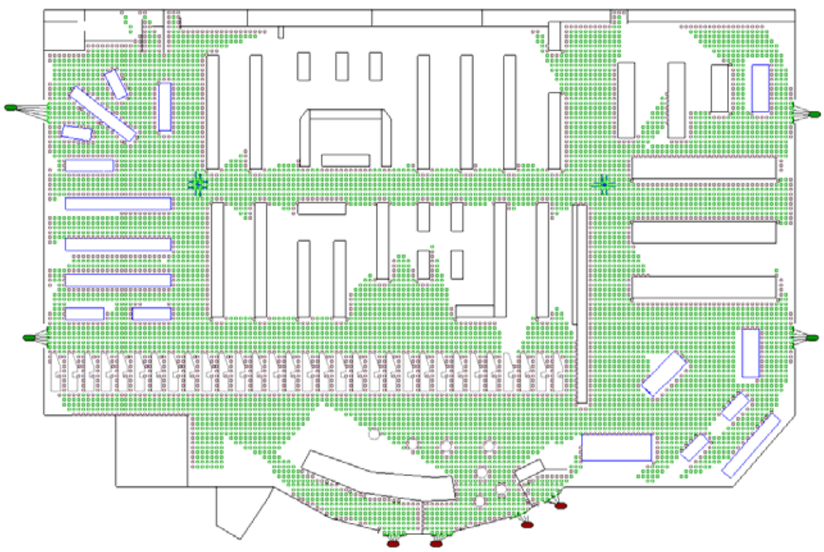


Figure 9.4: VCA coverage of the entire signage system.

The details of Scenario 3 and 4 are now described.

Scenario 3: The entire population have the same level of exit knowledge as in Scenario 1 but are now able to use signage information to wayfind to emergency exits. This will only occur if the agent falls within the VCA of a sign and is moving in an appropriate direction to be likely to see the sign. In this case, the agent is then given a 100% detection probability and a

100% acceptance probability (at each step within the VCA) and will follow the sign to the identified emergency exit if it is closer than the main exits. This scenario represents the current capabilities of the buildingEXODUS software and its signage model. Scenario 3 is divided into two sub scenarios: Scenario 3a examines the first set of exit signs only, and Scenario 3b examines both sets of exit signs.

Scenario 4: This scenario is similar to Scenario 3, but the data derived from the signage experiment (see Chapter 6, Chapter 7 and Chapter 8) is used to represent the signage detection probability and the compliance probabilities. It is noticed that unlike walls the supermarket shelving does not restrict an agent's view completely, i.e. the agent can look over the shelving. Therefore, it is appropriate to treat the supermarket geometry as open spaces rather than confined spaces. This means that when the agents are within the VCA of a sign and are moving in an appropriate direction relative to the sign, they will have a 38% chance of detecting the sign and if detected, a 97% chance of accepting the information and following the sign to an emergency exit (see Table 7.9). The 38% detection probability represents the probability of detection while in the VCA of the sign, and so the detection probability at each step while within the VCA is considerably smaller. Also, while the signs used in the simulation are larger than the signs used in the signage experiment, the detection probabilities of the smaller signs will be used in the simulations. Scenario 4 is divided into two sub scenarios: Scenario 4a examines the first set of exit signs only, and Scenario 4b examines both the first and second set of exit signs.

9.2.3 Simulation Results

Each scenario was run 10 times to produce a range of results. During each repeat simulation the individuals started from the same locations so that the influence of the signage system could be better assessed. Presented in Figure 9.5, Figure 9.6, Figure 9.7 and Table 9.1 are the mean values, along with the variation (± two standard deviations) for some of the key parameters generated from the simulations.

Table 9.1: Average evacuation performance of the scenarios simulated.

Scenario No.	Total evacuation time (s)	Average individual evacuation time (s)	Average congestion time (s)	Average distance travelled (m)	Average number of agents using emergency exits
1	183.7 ± 9.1	72.2 ± 1.2	38.3 ± 1.2	42.5 ± 0.1	0
2	81.6 ± 1.3	31.2 ± 0.4	12.4 ± 0.4	22.9 ± 0.1	678 ± 3
3a	153.2 ± 8.1	48.6 ± 1.9	20.8 ± 1.6	34.6 ± 0.5	226 ± 17
3b	97.9 ± 6.5	35.9 ± 0.8	12.9 ± 0.8	28.3 ± 0.2	420 ± 14
4a	177.7 ± 8.7	66.7 ± 2.7	34.0 ± 2.3	40.9 ± 0.6	43 ± 13
4b	147.3 ± 14.2	53.4 ± 2.6	24.3 ± 2.2	36.2 ± 0.8	167 ± 20

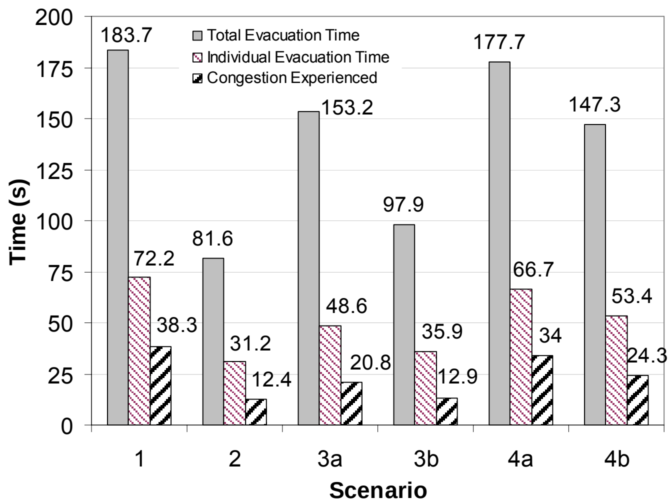


Figure 9.5: Average evacuation performance of the scenarios simulated.

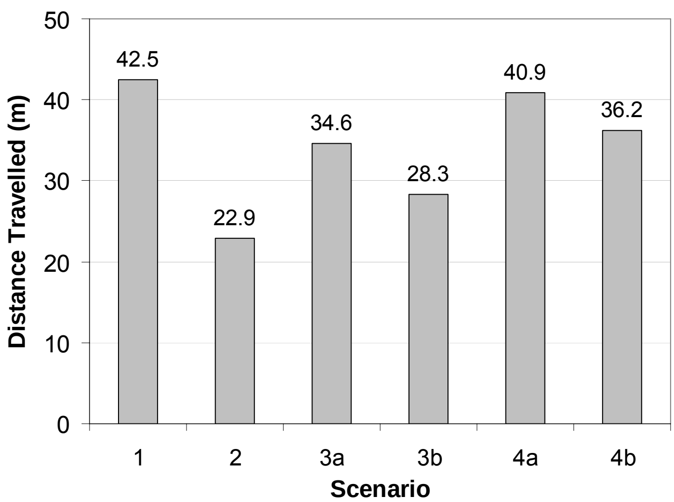


Figure 9.6: Average individual travel distance of the scenarios simulated.

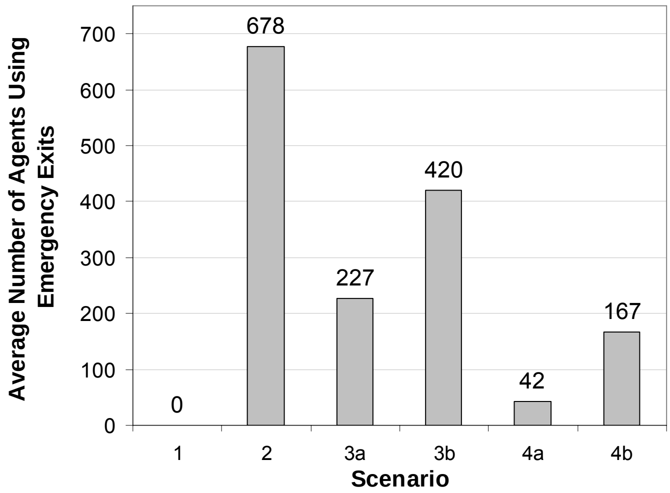


Figure 9.7: Average numbers of agents using emergency exits.

In Scenario 1, all the agents attempt to exit the store from the four main exits located in the front of the supermarket. The average travel distance in this case is 42.5 m. The large number of arrivals at the exits in the early stages of the evacuation soon exceeds the exit flow capacity and large crowds develop. As a result, agents spend 38.3 s on average in congestion (cumulative wait time), which accounts for 53% of their average individual evacuation time (72.2 s).

In Scenario 2, the agents are aware of all eight exits and so select their nearest exit to evacuate. In this case, 678 (67.8%) of the agents on average use the four emergency exits rather than the four main exits. As a result, the average travel distance is greatly reduced to 22.9 m. The total evacuation time is more than halved to 81.6 s. The amount of time wasted in congestion is also greatly reduced to just 12.4 s and represents some 39.7% of the average personal evacuation time. In a real emergency situation, some of the occupants are expected to utilise the emergency exits, so an actual evacuation of the supermarket is expected to require a total evacuation time between the results of Scenario 1 and 2, i.e. between 184 s and 82 s.

In Scenario 3a and 3b, agents who are within the VCA and are travelling in a direction in which it is physically possible to see a sign have a 100% probability that they will detect this sign and a 100% probability that they will follow the direction of the sign if it indicates a nearer exit. For Scenario 3a (the signs indicating the emergency exits can be seen from 32.4 % of the floor space) 22.6% of the agents use the emergency exits. The total evacuation time is reduced to 153.2 s which is 16.6% smaller than the result for Scenario 1 (agents only utilise the main exits), while this result is still 88.7% larger than the evacuation time in Scenario 2 (all agents utilise their nearest exit). For Scenario 3b (the signs indicating the emergency exits can be seen from 50.4 % of the floor space) 42.0% of the agents use the emergency exits. The total evacuation time is noticeably reduced to 97.9 s which is 46.7% smaller than the result for Scenario 1, while this result is only 20.0% larger than the evacuation time in Scenario 2. The 100% detection and compliance probabilities employed in Scenario 3a and 3b result in a large number of agents utilising the emergency exits. When the VCA coverage indicating the emergency exits increases from 32.4% (Scenario 3a) to just about half of the geometry (Scenario 3b), the average travel distance, average cumulative wait time and average individual evacuation time significantly decrease compared with those values found in Scenario 1 and are just slightly higher than those values found in Scenario 2.

In Scenario 4a and 4b, the average signage detection probability is reduced to 38%. Thus while an agent is within the VCA and is travelling in a direction in which it is physically possible to see the sign, there is only a 38% chance that the sign will be detected. Again, it must be emphasised that this represents the total probability that the sign will be detected while the agent is within the VCA of the sign and not the probability per step while within the VCA of the sign. If the agent will travel a total of *N* steps in the VCA, the detection probability at each step is

$$P_s = 1-(1-0.38)^{1/N} . \quad \textbf{(Equation 9.1)}$$

Once detected, there is a 97% chance that the agent will follow the sign. This detection probability is very low and as a result, considerably fewer agents utilised the emergency exits as compared with Scenario 2 and even Scenario 3a/3b using the same signage system. For Scenario 4a (the signs indicating the emergency exits can be seen from 32.4% of the floor space) only 4.3% of the agents use the emergency exits. This results in a considerable increase in the average total evacuation time (177.7 s), average individual evacuation time (66.7 s), average cumulative wait time (34.0 s) and average travel distance (40.9 m) compared with Scenarios 2 and 3a; besides, these values are just slightly lower than those of Scenario 1. However, given the additional two groups of exit signs added in Scenario 4b (the signs indicating the emergency exits can be seen from 50.4% of the floor space) the percentage of the agents using the emergency exits increases to 16.7%. The average total evacuation time for Scenario 4b then decreases to 147.3 s. Although this value is still 50.5% higher than that of Scenario 3b using the same signage system with 100% probability of detection, it is 19.8% lower than for Scenario 1 (all agents utilise only the main exits).

The results from Scenario 3a/3b and Scenario 4a/4b indicate that exit signs can be useful in directing people to emergency exits and hence reducing egress times for large structures with complex interior layouts (against Scenario 1). In the ideal situation (i.e. Scenario 3a and 3b), where signs have a 100% detection (and compliance) rate and cover sufficient building space, evacuation times could be reduced to a level comparable to the situation in which all occupants had perfect knowledge of the exit positions (i.e. Scenario 2). However, in the more realistic situation (i.e. Scenario 4a and 4b), the low detection rate associated with signs greatly constrains the possible improvements in egress times that may be achieved.

9.3 Case Two

The first demonstration case simulated the interaction between occupants and signage system in a large-scale building with a simple structure. Since this case examined the application of the signage model in a relatively open space, the second demonstration case is designed to examine the impact of signage upon occupants in a relatively confined built environment with a complex structure.

9.3.1 Definition of Geometry and Test Population

The geometry used in this case is a single storey building which consists of a number of small rooms, halls and corridors (see Figure 9.8). The building has four exits: one main exit (measuring 2 m in width) located in the middle and three emergency exits (measuring 1 m in width) located at three corners. The total available area where the simulated agents can manoeuvre within the building has been calculated to be approximately 720.3 m^2.

The geometry is populated with 300 agents (155 males and 145 females) to represent a general population of building occupants. They are randomly generated using the standard buildingEXODUS default options with travel speeds ranging from 1.2 m/s to 1.5 m/s and located throughout the geometry. For the purpose of these demonstrations it is assumed that the population is fully mobile (no movement disabilities) and they randomly require between 0 and 30 seconds to respond to an evacuation alarm. It is also assumed that the entire population is only familiar with the main entrance/exit (except in Scenario 2 described below). The average agent height is assumed to be 1.75 m when calculating the coverage of the VCAs of the signs.

Figure 9.8: The geometry of the test building.

9.3.2 Simulation Scenarios

Five scenarios are examined. Scenario 1 and 2 are two base cases with no representation of the interaction between the agents and the signage system. They are used to compare with the other three scenarios which include the interaction. The details of Scenario 1 and 2 are now described.

Scenario 1: The entire population utilise the main exit only throughout the simulation, while all emergency exits and signage information are ignored.

Scenario 2: The entire population utilise every available exit, while all signage information is ignored too. The agents' choice of exit is simply based on an estimation of the distance to all available exits, and they will try to use the nearest exit leading to the outside.

Scenario 1 represents a base case situation which is a plausible worst egress scenario as the additional egress capacity provided by the emergency exits are not utilised. In contrast, Scenario 2 represents a best case situation or an optimal case in which every agent has complete knowledge of the layout of the building. The likely results of a real evacuation are expected to fall between the results of Scenario 1 and Scenario 2.

Scenario 3, 4 and 5 simulate the interaction between the agents and the exit signs positioned in the building. Sign S1 is positioned immediately above Exit 1. Since Exit 1 is located at a corner with limited visual access (Sign S1 is only visible from a small area measuring 4.5 m^2), three additional signs, S2, S3 and S4 are positioned in the north-east corridor to indicate the exit path via Exit 1. Sign S5 is positioned right above Exit 2. Since Sign S5 has a limited VCA coverage (11.5 m^2) too, Sign S6 is installed nearby to increase the chance of Exit 2 being noticed. Sign S7 and S8 are positioned immediately above the main exit and Exit 3 respectively. Sign S9, which is only available in Scenario 5, is positioned in the south-west hall to indicate the location of Exit 3. All of the signs are externally illuminated and subject to a vertical illuminance of 100lux. They are placed at a height of 2.2 m above the floor. The graphical symbol on each sign is assumed to be 75 mm in height producing a maximum visibility distance of about 13 m [BS5499-4:2000]. The VCA of each sign is circular in shape as determined in Section 8.2.1, Chapter 8. Since these signs are positioned primarily in the corridors and halls, no furnishings are taken into account when calculating the VCAs.

The details of Scenario 3, 4 and 5 are now described.

Scenario 3: The entire population have the same level of exit knowledge as in Scenario 1 but are now able to use signage information to identify emergency exits. This will only occur if the agent falls within the VCA of a sign and is moving in an appropriate direction to be likely to see the sign. In this case, the agent is then given a 100% detection probability and a 100% compliance probability at each step within the VCA of the sign. The agent will follow the sign to the identified emergency exit if it is closer than the main exit.

Scenario 4: This scenario is similar to Scenario 3 but the new signage model (see Chapter 8) is used to determine the likelihood of the signs being detected and used during the simulation. The detection and compliance probability of each sign are calculated individually according to the VCA coverage of that sign (see Table 9.2). In general, if a sign is located in a confined space, the chance of the sign being detected is relatively higher than that of a sign located in an open space. However, once detected, the acceptance probabilities in both cases are similar. Also, it should be pointed out that the signs used in the simulation are approximately the same size as those used in the signage experiment. The detection and acceptance probabilities of these signs should be close to those measured in the experiment given the influence of size factor is ruled out.

Table 9.2: Model prediction of the detection and compliance probabilities of each sign.

Sign	Associated exit	VCA (m^2)	VCA coverage	Detection probability	Compliance probability
S1	Exit 1	4.5	3.4%	75%	96%
S2	Exit 1	24.0	18.1%	68%	96%
S3	Exit 1	25.3	19.0%	67%	96%
S4	Exit 1	20.3	15.3%	70%	96%
S5	Exit 2	11.5	8.7%	75%	96%
S6	Exit 2	38.8	29.2%	58%	96%
S7	Main Exit	44.0	33.2%	55%	96%
S8	Exit 3	114.0	85.9%	38%	96%
S9*	Exit 3	123.3	92.9%	38%	96%

* Sign S9 is only available in Scenario 5.

Scenario 5: This scenario is similar to Scenario 4 but an additional sign, Sign S9, is added in the south-west hall to improve the signage system.

9.3.3 Simulation Results

Each scenario was run 10 times to produce a range of results. During each repeat simulation the individuals started from the same locations so that the influence of the signage system could be better assessed. Presented in Figure 9.9, Figure 9.10, Figure 9.11 and Table 9.3 are the mean values, along with the variation (± two standard deviations) for some of the key parameters generated from the simulations.

Table 9.3: Average evacuation performance of the five scenarios.

Scenario No.	Total evacuation time (s)	Average individual evacuation time (s)	Average congestion time (s)	Average distance travelled (m)	Average number of agents using emergency exits
1	136.1 ± 2.8	72.2 ± 1.4	39.4 ± 1.4	18.9 ± 0.2	0
2	77.0 ± 1.6	37.8 ± 0.6	12.2 ± 0.6	11.0 ± 0.0	141 ± 1
3	90.3 ± 4.4	42.0 ± 1.2	14.9 ± 1.2	12.5 ± 0.2	110 ± 5
4	112.6 ± 3.8	54.5 ± 1.8	25.1 ± 1.6	15.0 ± 0.4	56 ± 9
5	99.2 ± 5.2	46.6 ± 2.2	18.0 ± 2.0	14.2 ± 0.4	88 ± 10

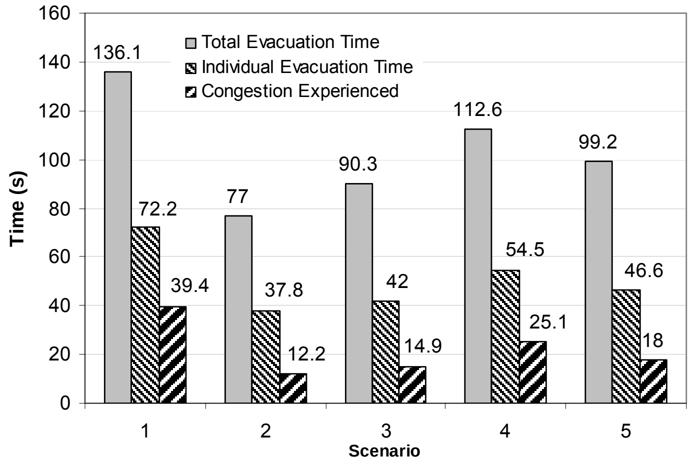


Figure 9.9: Average individual travel distance of the scenarios simulated.

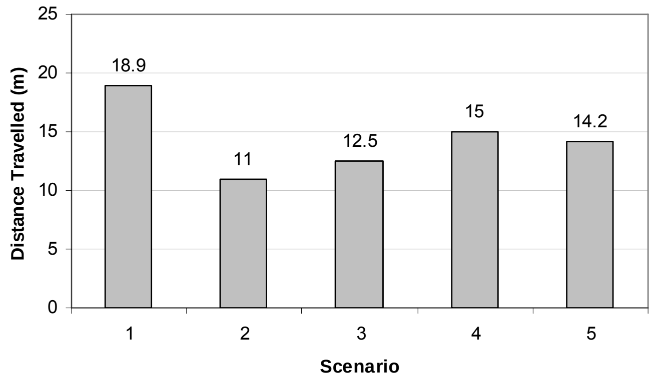


Figure 9.10: Average individual travel distance of the scenarios simulated.

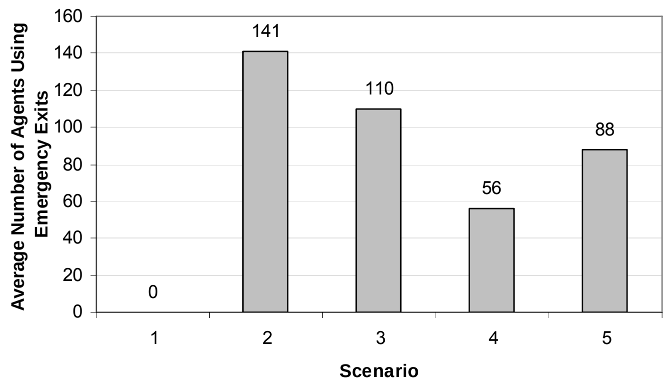


Figure 9.11: Average numbers of agents using emergency exits.

In Scenario 1, the evacuation of the entire population from the building is through the main exit located in the middle of the building only. The large number of arrivals at the main exit in the early stages of the evacuation soon exceeds the exit flow capacity and large crowds develop around this exit. As a result, on average agents spend 39.4 s in congestion, which accounts for 54.6% of their average individual evacuation time (72.2 s). This scenario represents the worst case as the other three exits are not utilised.

An efficient solution to the problem presented in Scenario 1 is to let some of the agents resort to the other exits to avoid or at least reduce the congestion built up at the main exit. In an ideal situation simulated by Scenario 2, all agents know the layout of the building and the location of all exits, so that they can choose a nearest exit to escape. Figure 9.12 shows the division of the geometry into four zones according to an estimate of travel distance. The zone in which the agents are initially located determines the exit they will use to escape. For instance, any agents who start from Zone 1 will try to exit the building through Exit 1 as it is the nearest exit. In Scenario 2, the average travel distance is greatly reduced to 11.0 m compared with 18.9 m in Scenario 1, showing that the agents are making use of their nearest exits. Also, the total evacuation time is decreased to 77.0 s, nearly a half of that for Scenario 1. The amount of time wasted in congestion is also greatly reduced to just 12.2 s and represents 32.3% of the average personal evacuation time.

It should be pointed out that Scenario 2 is not the most optimal case, as there is still small scale congestion built up around the main exit while the other three exits have cleared at around 60 s. However, to further reduce the evacuation time, the agents require more information to make a better choice, which is beyond the scope of this case study.

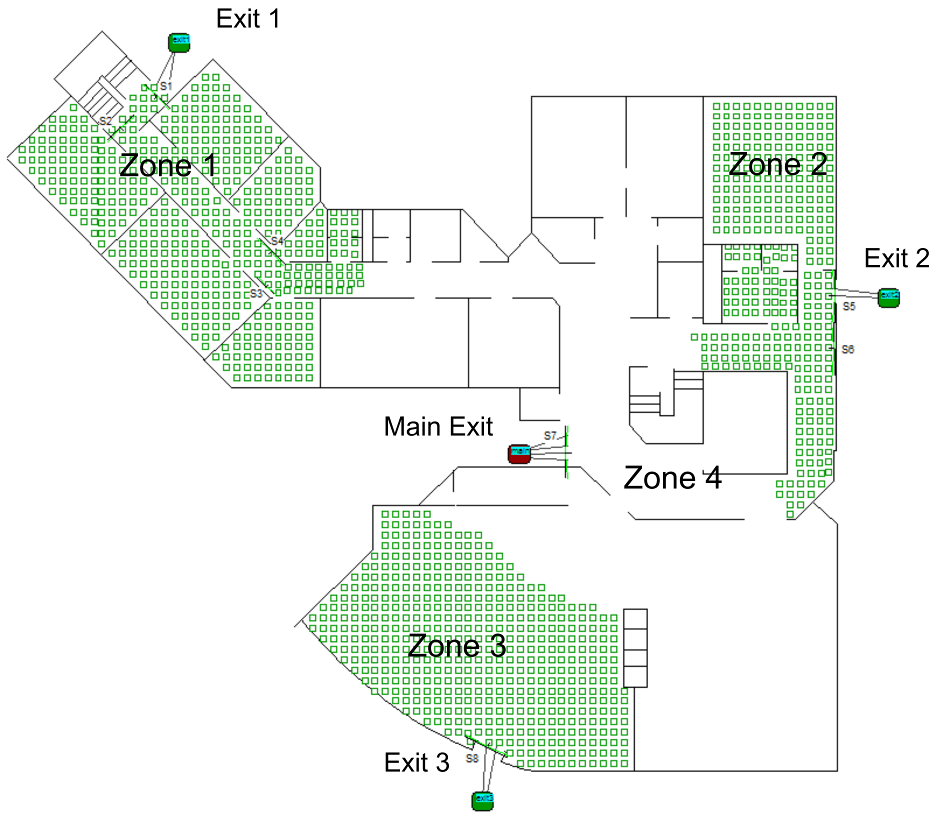


Figure 9.12: The four zones and the associated four exits.

Scenario 1 and 2 represent two extreme cases regarding the level of exit knowledge the agents rely on to make an exit selection. From knowing the main exit only in Scenario 1 to knowing every exit in Scenario 2, the change of the level of the exit knowledge among the agent population results in a significant improvement in all key evacuation parameters. In a realistic situation, some of the unfamiliar occupants are expected to detect one or more exit signs and gain additional exit knowledge to make an adaptive exit selection during an evacuation. Therefore, any real evacuation of the building is expected to require a total evacuation time between the results of Scenario 1 and 2. The efficiency of occupants obtaining and using exit knowledge from an information source like the signage system influences whether the results of an evacuation are close to the worst case (Scenario 1) or the best case (Scenario 2). The effectiveness of a signage system is examined through the other three scenarios which allow the simulated agents to detect exit signs and use the information perceived to make an adaptive exit selection.

Firstly, the effectiveness of signage system upon the evacuating agents is examined through Scenario 3 which implements an ideal interaction between the agents and the signs. During the simulation, agents who are within the VCA and are travelling in a direction in which it is physically possible to see the sign have a 100% probability that they will detect the sign and a 100% probability that they will actually follow the sign if it leads to a nearer exit. The 100% probability of detection and compliance results in a large number of agents utilising the emergency exits. On average 36.7% of the agents utilise the emergency exits. The total evacuation time is reduced to 90.3 s which is 33.7% smaller than the result for Scenario 1 (agents utilise the main exit only), while this result is only 17.3% larger than the evacuation time in Scenario 2 (agents utilise all exits).

Table 9.4: The number of agents using the corresponding exit in each exit zone.

Zone	1	2	3	4
Number of agents in each exit zone prior to evacuation	55	32	54	159
Number of agents using corresponding exit in Scenario 1	0	0	0	300
Number of agents using corresponding exit in Scenario 2	55	32	54	159
Number of agents using corresponding exit in Scenario 3	55	25	30	190
Number of agents using corresponding exit in Scenario 4	36	17	3	244
Number of agents using corresponding exit in Scenario 5	35	16	37	212

Secondly, the effectiveness of signage system upon the evacuating agents is examined through Scenario 4 and 5 which simulate a more realistic interaction between the agents and the signs than Scenario 3. In these two scenarios, the signage detection and compliance probabilities are determined by the new signage model and vary with the VCA coverage of the signs.

In Scenario 4, 18.7% of the agents who are originally located in Zone 1, 2 and 3 see the signs and decide to use the corresponding emergency exits. This is almost half of the rate (36.7%) measured in Scenario 3. If the rate measured in each zone is compared between the two scenarios, the corresponding rates measured in the three zones are 100%, 78.1% and 55.6% for Scenario 3, and the rates are 64.5%, 53.1% and 5.6% for Scenario 4. The decrease in the rates of detecting and following signage during evacuation is expected since much lower and more representative signage detection probabilities are implemented in Scenario 4. However, the degree of decrease is unequal among the three zones. It is apparent that the rate in Zone 3 drops more significantly than those of Zone 1 and 2. This could be due to the fact that the sign in Zone 3 is located in a relatively open space, while the signs in Zone 2 and 3 are located in much narrow corridors. According to the new signage model, the detection probability of the sign in Zone 3 is smaller than those of the signs in Zone 1 and 2 because of larger VCA coverage. Apart from the difference in the VCA coverage, it is also noticed that the relative orientation between the initial agent flow towards the main exit and the signs are different in the three zones. In Zone 1 and 2, at least two signs are located along the agents' path towards the main exit, while in Zone 3 all of the agents are turning away from the sign from the beginning (see Figure 9.13).

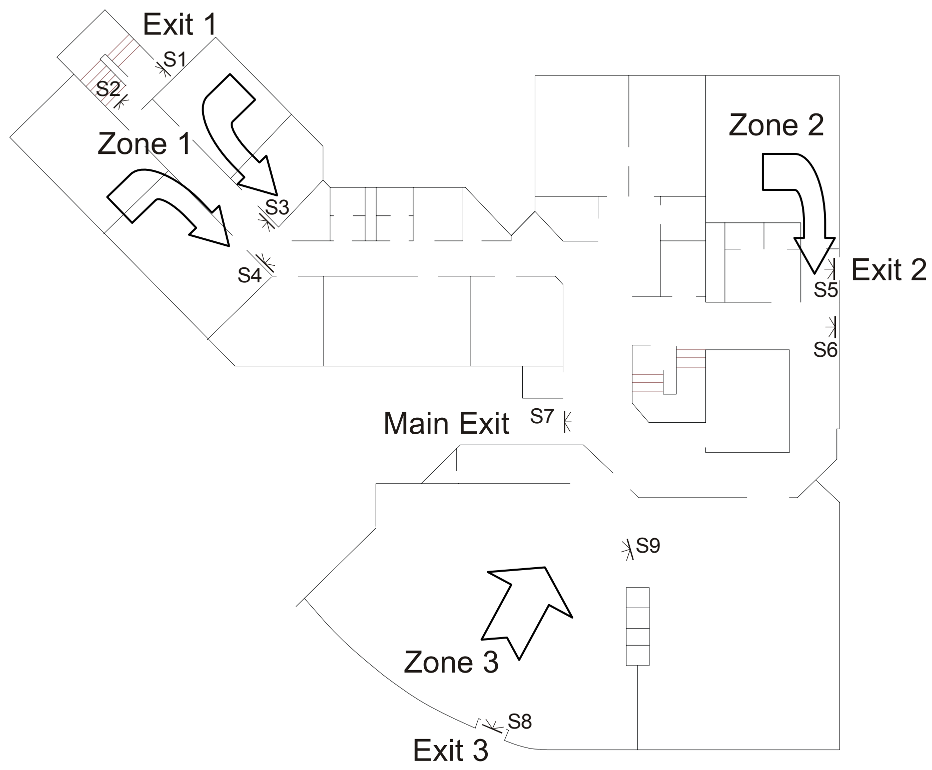


Figure 9.13: The initial agent flow towards the main exit.

In order to examine the two factors which potentially cause the low rate of utilising signage in Zone 3, an additional sign, Sign S9, is added in Zone 3. This sign is facing the opposite direction in which the agents in Zone 3 move towards the main exit. This modified signage system is examined in Scenario 5 with the same settings as Scenario 4.

The results of Scenario 5 show that on average 68.5% of the agents in Zone 3 now detect the signs and redirect to Exit 3. This is a significant improvement compared with Scenario 4 (5.6%) and even Scenario 3 (55.6%) which represents an ideal situation (100% detection probability). These results confirm the influence of the two factors identified previously, i.e. Sign S8 is less efficient than the other signs because it is located in an open space and it is facing in the same direction in which the agents move towards the main exit. These results also suggest that despite the low detection rate of signage in an open space, the effectiveness of signage systems can be improved by carefully planned installation of exit signs.

9.4 Summary

When assessing the evacuation capability of a building using computer simulation, a common approach is to establish an upper and lower limit to begin with, and then investigate the likely evacuation performance taking interested influencing factors involved in the evacuation into account. Typically the scenario for the upper limit involves all the agents utilising the main exits only while the scenario for the lower limit involves all the agents utilising all available exits. These two scenarios can be simulated by directing occupants to the main exits and the nearest exits respectively. In a real emergency situation, occupants, especially those who are unfamiliar with the structure, may be expected to utilise the signage systems to assist them in wayfinding. Even those who are familiar with the building layout may still have to utilise the signage systems to identify an egress route and exit door intended for emergency use. Therefore, the signage systems may influence occupant's choice of exit route/exit door, and consequently the effectiveness of the signage systems may influence whether the evacuation performance is close to the upper limit or the lower limit.

The interaction between occupants and signage systems within the built environment was studied through experimentation (see Chapter 6 and Chapter 7). Experimental findings confirmed that people may not detect and utilise a sign even if the sign is physically visible. This is due to the impact of various influencing factors that are involved in the interaction between occupants and signage. These findings have led to the development of a new signage model (see Chapter 8). The model captures the main factors and represents their influence during the simulation of the interaction. The model determines when, where and how likely occupants perceive and utilise exit signs during an evacuation. This model was then implemented within the buildingEXODUS evacuation model to investigate the impact of exit signs may have on evacuating occupants.

In this chapter, the application of the signage model was examined through two simulation cases of evacuation from two different types of building: one large-scale building and one small, but complex building. The simulated agents are initially assumed to be unfamiliar with the building layout in both cases so that they are only aware of the main entrances/exits. All the agents respond to a call for escape from the buildings through the nearest exits they know during the simulation. Several scenarios were examined where the agents were given no awareness (to produce the upper limit), full awareness (to produce the lower limit) and dynamic awareness (obtained through the interaction with the signage system) of the other available exits respectively. In addition, the dynamic awareness was simulated in two ways.

The first way represents the interaction between occupants and signs in an ideal situation where occupants have a 100% detection rate and a 100% compliance rate if they are able to see the signs. The second way represents a more realistic situation where both rates are based on the experimental findings. The evacuation performance measured in each of these scenarios was then compared.

It was found through these simulation cases that for large and complex structures signage systems can be useful in directing unfamiliar occupants to emergency exits, and hence reducing egress times. In the ideal situation in which the agents have both a high detection rate and compliance rate, the evacuation performance is comparable to that achieved in the situation where the agents have a full knowledge of all the exits. However, in the more realistic situation simulated by the new signage model based on the experimental findings, the low detection rate associated with the signs greatly constrains the possible improvements in egress times that may be achieved.

It was also found that the effectiveness of signage systems is influenced by the installation of signs inside the buildings. First of all, the VCA of the signs must cover an adequate area to provide directional information to building occupants. In general, exit signs positioned above exit doors are not sufficient to provide necessary coverage area due to the limit in maximum viewing distance and complex internal layout; additional signs are normally required at locations where it is not possible to see an exit door. Secondly, the effectiveness of signs is influenced by the nature of the space where signs are positioned. If the other conditions remain the same, signs positioned in a relatively open space have a lower probability of being perceived and used than those positioned in a relatively confined space. Finally, the effectiveness of signs is influenced by the relative orientation between the signs and the potential occupant direction of travel, as signs facing occupants are more likely to be seen than those that fall aside of their direction of travel.

In summary, a big gap usually exists between the upper and lower limit of the evacuation capability of a building when building occupants use the main exits and all available exits respectively in evacuations. Signage systems, as an important means to assist evacuating occupants, influence the likely evacuation performance between the limits. The application of the new signage model in evacuation simulation can help assess the likely evacuation performance given a specific signage system in the building and improve the design of the signage system.

Chapter 10

The Visibility of Exit Signs in Smoke

During an evacuation from a fire, the presence of fire generated hazards is not only a threat to an evacuee's physical well-being, but it also influences their evacuation behaviour. Smoke, in particular, can impair an evacuee's visual perception, obscure their view and consequently, reduce their ability to discern wayfinding clues. In order to correctly estimate the conditions for a safe evacuation, it is important to take account of the reduction of the visibility of signage through smoke. The representation of this impact was previously lacking in existing evacuation models (Section 2.4.2.2, Chapter 2). This chapter presents a method to calculate the reduction of the Visual Catchment Area (VCA) of the sign in smoke accordingly.

10.1 Represent the Obscuration Effect of Smoke upon the Visibility of Signage

The ability of evacuees to perceive information from exit signs during an evacuation from a fire is often impaired due to reduced visibility through smoke (Section 2.3, Chapter 2). A key study on human visibility through smoke is Jin's experimental research on the factors affecting visibility [Jin, 1978, 1997, 2008]. He found that human visibility levels at both the obscuration threshold of an exit sign and the legible threshold of text on the sign are reduced as the smoke density increases. He concluded, according to the data collected, that the impact of smoke upon the visibility of signage can be expressed as a constant product of the visibility distance and the smoke density. Jin's findings are essential for their potential application in representing the impact of smoke upon the visibility of signage in modelling. However, Jin's study did not take account of the other factors affecting signage visibility distance, such as the size of sign and the viewing angle; besides, his empirical equation mostly takes account of homogeneous smoke.

The influence of the size of sign and the viewing angle upon the visibility of signage has been addressed in Chapter 4 and Chapter 5. It was found through theoretical analysis and experimental study that in a clear and well lit environment, the VCA of a sign measured by the legible threshold of the text on the sign has a circular representation. The diameter of this circle is equal to the maximum viewing distance when the sign is viewed perpendicularly.

Given that the visibility of signage in a clear environment and through smoke has been addressed separately, an attempt is made to combine the two approaches and incorporate an adapted Jin's model [1978, 1997, 2008] into the current VCA sub-model. This combined approach allows the estimation of the impact of smoke upon the visibility of signs in evacuation modelling, taking account of the size of sign, the viewing angle and inhomogeneous smoke distribution.

Figure 10.1 shows three occupants in a single room facing a sign positioned at the bottom right corner. At the beginning when no fire hazard is present, a circular VCA depicted by the solid circle represents the visibility limits of the sign in a clear environment: P1 standing outside the VCA is unable to read the sign; while P2 and P3 standing inside the VCA are able to discern the sign. When an inhomogeneous distribution of smoke is present, an irregular gray area depicted by the broken curve represents a reduced VCA due to the obscuration effect of the smoke. At this moment, only P3 standing inside the reduced VCA is still able to discern the sign. So the boundary of the VCA is determined by both the visibility limits of the sign in a clear environment and the impact of smoke.

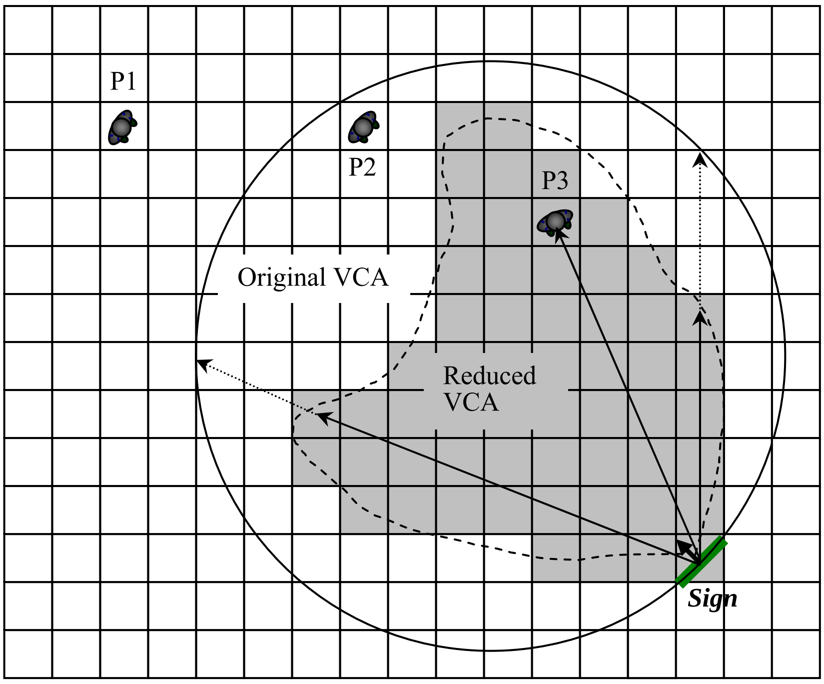


Figure 10.1: The VCAs of a sign in a clear environment and in smoke.

The impact of smoke is assessed through an adapted Jin's model, which integrates the product of local extinction coefficient $C_s(x)$ and the segment length dx along the line of sight from the sign for a continuous geometry. For the sign to be visible through smoke, the integration must satisfy

$$\int C_s(x)dx \leq K \text{ ,} \qquad \textbf{(Equation 10.1)}$$

where K is the constant obtained from the Jin's model [1978, 1997, 2008].

The buildingEXODUS model is capable of utilising the results generated by fire simulation to represent the development and spread of fire atmosphere during simulation (Section 3.3.2.3, Chapter 3). The model is also capable of representing the visibility of exit signs through the introduction of the concept of VCA (Section 3.3.2.1, Chapter 3). The combination of these features and Equation 10.1 makes it possible to represent the visibility of an exit sign in a fire atmosphere in evacuation simulation.

buildingEXODUS represents a geometry by two-dimensional grids (Section 3.2, Chapter 3). An occupant occupies a node in the geometry. The position of the sign is also linked with a node. The line of sight from the occupant to the sign links the two nodes occupied and intersects a series of nodes in between. Equation 10.1 is then transformed to its discrete form

$$\sum_{i=0}^{n}(C_s)_i \cdot x_i \leq K \text{ ,} \qquad \textbf{(Equation 10.2)}$$

where $(C_s)_i$ is the local extinction coefficient of the i^{th} node on the line and x_i is the length of segment intersecting the node.

Whether the exit sign is discernable from where the occupant is located is determined by two criteria: (1) the occupant location must be within the original VCA of the exit sign measured in a clear environment and (2) the condition in Equation 10.2 must be met if smoke is present.

The above method requires significant computational power to update all VCA along with the development of the fire in a simulation. Considering some cases in which the local smoke distribution is homogeneous within small areas comparable to the VCAs, the method can be simplified by using the mean smoke density for signage visibility distance calculation, i.e.

$$V \cdot C_{mean} = K \text{ .} \qquad \textbf{(Equation 10.3)}$$

where C_{mean} is the arithmetic average of the extinction coefficient of all nodes inside the VCA and V is the maximum visibility distance through smoke in all directions. This simplified method is useful when the level of simulation accuracy can be reduced in favour of faster simulations.

10.2 Demonstration Cases

Two cases are described in this section to demonstrate the model presented in Section 10.1 and the impact of smoke upon the visibility of exit signs. The first case is a simple one which includes an exit sign in a room with homogeneous smoke. This case shows the area of the VCA at several levels of smoke concentrations. The second case is more complicated and is based on the reproduction of a real fire. This case involves multiple exit signs in a complex built environment and it shows the reduction of the effective covering area of these exit signs with the reproduction of the fire scenario.

10.2.1 Case One

This case involves an exit sign positioned at the middle top of an empty square room. The room measures 35 m both in width and depth. Two types of exit sign, a reflecting sign (K=3) and a light-emitting sign (K=8), are examined separately at the same location. Initially, the room is smoke free. Both signs have a maximum viewing distance of 30 metres and a corresponding VCA of 707.5 m^2 in area (see Figure 10.2).

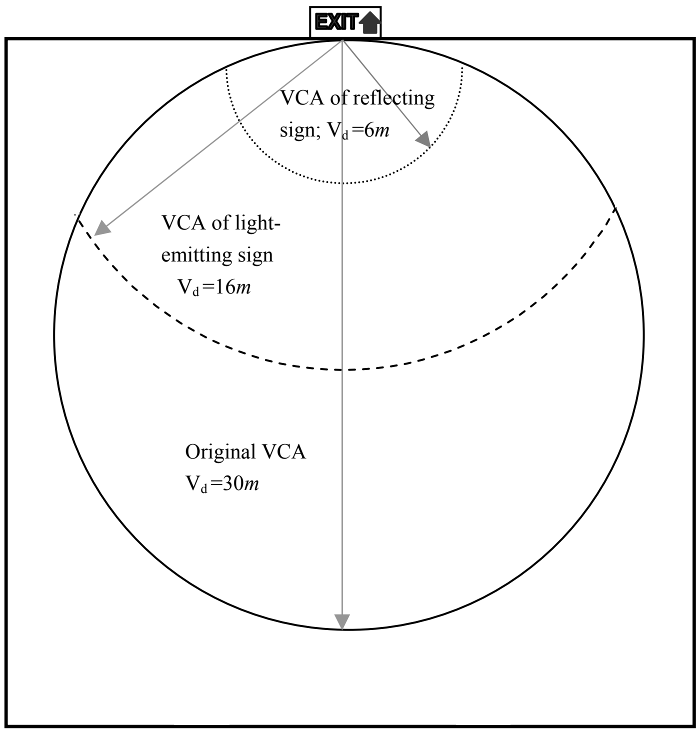


Figure 10.2: The VCAs in a clear environment and in smoke.

The room is then filled with well mixed smoke. The smoke concentration measured in the extinction coefficient increases from 0.1/m to 2.0/m step by step. Table 10.1 lists the corresponding area of the reduced VCA and the maximum visibility distance of the two exit signs predicted by the VCA sub-model (using Equation 10.3) at each stage. Figure 10.2 shows the shape and size of the VCAs of the light-emitting sign (the broken curve) and the reflection sign (the dotted curve) in a smoke of 0.5/m along with the original circular VCA.

Table 10.1: The VCA and the visibility distance of the two types of exit sign in smoke.

Smoke Concentration (/m)		0	0.1	0.2	0.5	0.7	1.0	1.2	1.5	2.0
Reflecting Sign (VC=3)	VCA (m^2)	707.50	707.50	277.75	49.75	26.75	12.5	8.25	5.00	2.75
		~	100%	38.98%	7.03%	3.78%	1.77%	1.17%	0.71%	0.39%
	Distance (m)	~	30.00	15.00	6.00	4.29	3.00	2.5	2.00	1.50
Light-emitting Sign (VC=8)	VCA (m^2)	707.50	707.50	707.50	308.00	172.25	87.50	61.50	40.75	22.50
		~	100%	100%	43.53%	24.35%	12.37%	8.69%	5.76%	3.18%
	Distance (m)	~	*30.00**	*30.00**	16.00	11.43	8.00	6.67	5.33	4.00

* The maximum visibility distance is determined by the size of the sign.

The reduction of the VCA with the increase of smoke density is more clearly shown in Figure 10.3. There is a step decrease in the VCA of both signs when the smoke density increases from 0.1/m to 0.5/m. The VCA of the reflecting sign drops by 93.0% from 707.50 m^2 to 49.75 m^2. The VCA of the light-emitting sign drops by 56.5% from 707.50 m^2 to 308 m^2. It is apparent the light-emitting sign performed better than the reflecting sign in a smoke of 0.5/m, as the former still covers up to 43.5% of its original VCA, whereas the reflecting sign covers less than 10% of its original VCA. The decrease of the VCA steps down with a further increase in smoke density from 0.5/m to 2/m.

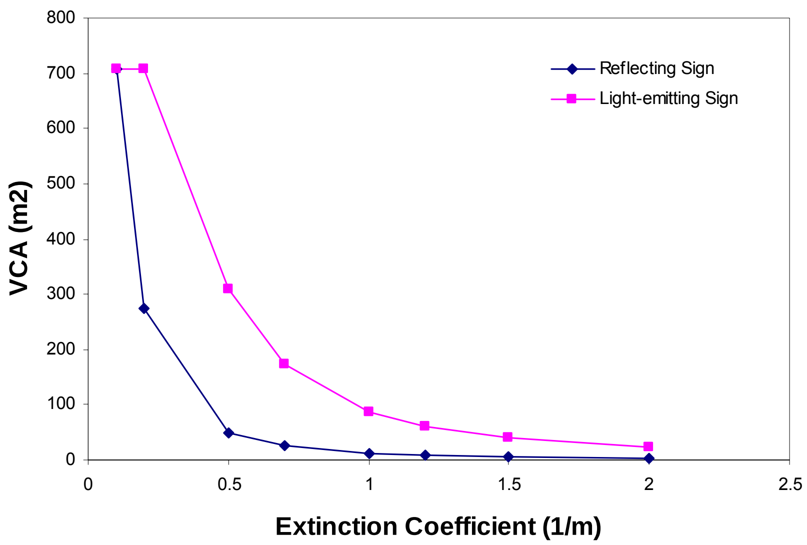


Figure 10.3: The decrease of the VCA of the two signs with the increase of smoke density.

A similar relationship between the maximum visibility distance of the two signs and the smoke density can be seen in Figure 10.4. With the increase of smoke density from 0.1/m to 0.5/m, the visibility of the reflecting sign drops 80% from 30 m to 6 m; the visibility of the light-emitting sign drops 46.7% from 30 m to 16 m. The visibility distance of both signs drops continuously to 1.5 m and 4.0 m respectively when the smoke density increases to 2.0/m, effectively making both of them discernable only by very close inspection.

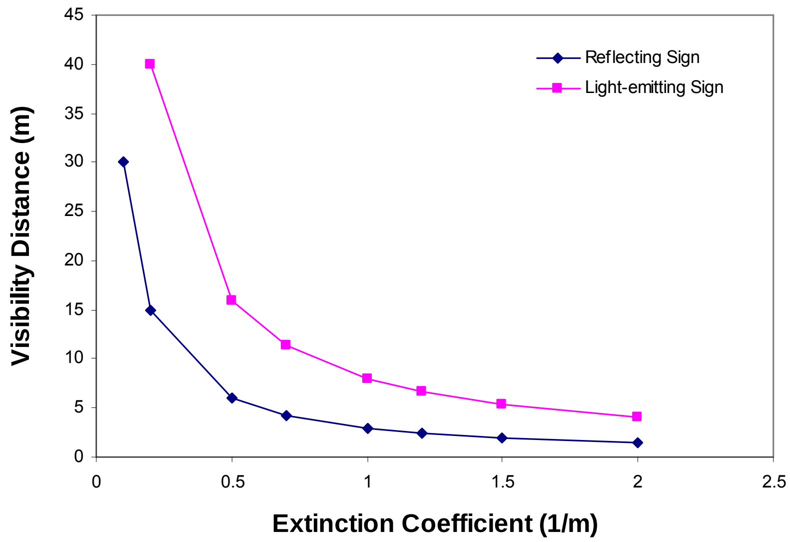


Figure 10.4: The relationship between the maximum visibility distance and smoke density.

10.2.2 Case Two

A fire occurred in The Station nightclub in Rhode Island, United States on the evening of February 20, 2003 [Grosshandler *et al*., 2005a, 2005b]. The club was a single-story building which was composed of the main bar room, the sunroom, the dart room, several restrooms, a dance floor, a kitchen, an office, and a storage area (See Figure 10.5). The building measured 32.8 m in width and 20.9 m in depth and had a footprint of 412 m^2. Initially the fire broke out when the soundproofing foam on the stage on the west end was ignited during the performance of a band. The fire spread quickly into the other part of the building. In spite of the fact that the building had four exits, most of the patrons only tried to evacuate through the front main entrance located on the north side. As a result, the door way was quickly jammed with people escaping from a fast growing fire. This was a key factor which contributed to a catastrophic loss of 100 human lives [Grosshandler *et al*., 2005a].

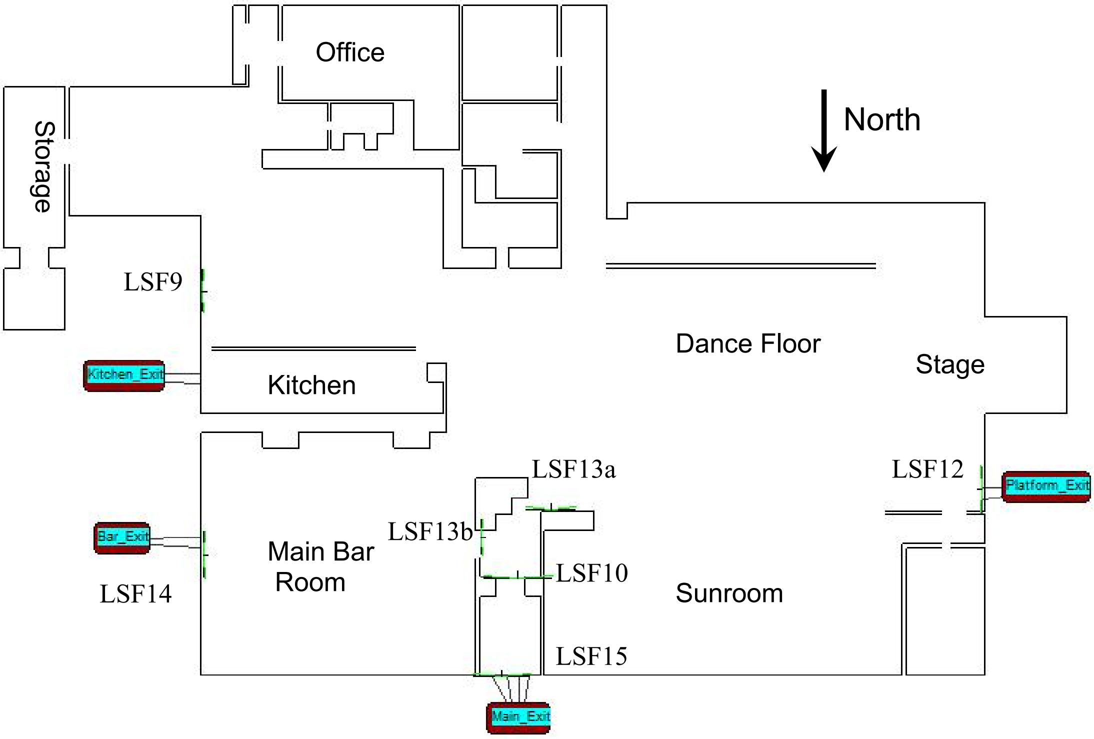


Figure 10.5: The geometry of The Station nightclub.

The four exits of The Station nightclub were the main entrance on the north wall, the barroom exit and the kitchen exit on the west wall and the stage exit on the east wall respectively. Exit signs, either illuminated or non-illuminated, were positioned above these doors. Given that the fire spread very fast in the building, effectively making the critical safe evacuation time in the event extremely limited, one would question why the signage system failed to encourage the patrons to escape via the alternative exits. This issue was briefly addressed in NIST's report from two perspectives [Grosshandler *et al*., 2005a]. Firstly, the use of exit signs and exits was inefficient due to the design of the building. The alternative exits were mainly used by those who were familiar with the nightclub. For example, a former club employee described the kitchen exit and the exit sign nearby in the following way [Grosshandler *et al*., 2005a]:

> "*It had an exit sign, but unless you're back in that area, you wouldn't know it. The way the club was shaped, it was out of the way.*"

Secondly, apart from the building design, the possibility of using exit signs during the evacuation was diminished quickly by the fact that these exit signs were quickly obscured by smoke, reducing the impact of the signs and making the alternative exits only available to those who were familiar with the layout of the nightclub.

The second demonstration case is based on a recent work [Galea *et al*., 2008] which reconstructed The Station nightclub fire using the SMARTFIRE fire simulation model [Ewer *et al*., 2007]. A full-scale simulation of the fire was carried out to predict the distribution of fire hazards including smoke in a 31-zone division of the original building (see Figure 10.6). The simulation starts right at the moment when the soundproofing foam on the stage was ignited, and generates the output at a time step of every 3.2 or 6.3 seconds. The simulation lasts for a total of 190 seconds which fully covers the critical safe evacuation time during the fire. The average smoke concentration at human body height (1.75 m) inside the building is shown in Figure 10.7.

Figure 10.6: The geometry of the nightclub is divided into 31 zones.

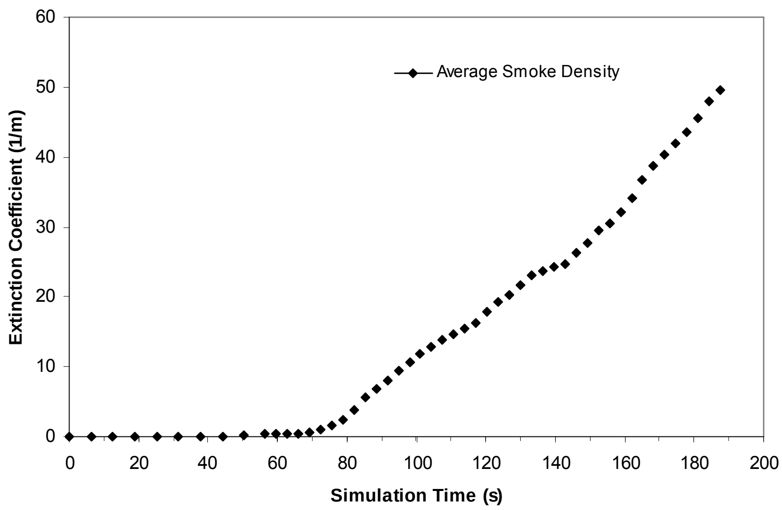


Figure 10.7: The average smoke density predicted by SMARTFIRE simulation.

It can be seen that, starting from the ignition, the average smoke density stays below 0.5 /m during the first period of 66 seconds. It then starts to increase almost linearly with the simulation time and reaches about 50/m at the end of the simulation.

The demonstration case utilises these results to estimate the effective coverage area of the exit signs positioned in the nightclub during the fire. It should be pointed out that the aim of this demonstration case is to show the visibility of the signs in the event; it does not address the likelihood that the evacuees would perceive the signs and how they would respond accordingly.

According to NIST's report [Grosshandler *et al*., 2005a, 2005b], there had been seven exit signs installed inside the nightclub (see Figure 10.5). The locations and illumination status of these signs are listed in Table 10.2.

Table 10.2: Exit signs installed in The Station nightclub.

Exit Sign	Location	Illuminated
LSF 9	An exit sign located near the rear bar; it appears to be pointing toward the kitchen exit door.	Unknown
LSF 10	An exit sign above the door that leads from the ticket area to the front vestibule.	No
LSF 11 / LSF 12	An exit sign above the platform door before February 20, 2003. The sign is clearly illuminated.	Yes
	An exit sign above the platform door on February 20, 2003. The sign which is a duplicate of LSF 11 does not appear to be illuminated, i.e. the exit sign may not have always been illuminated.	No
LSF13(a/b)	Two exit signs. One located in the main floor area with an arrow towards the ticket area and another above the ticket area doors leading to the front vestibule.	Yes
LSF14	An exit sign over the left side main bar area exit door.	Yes
LSF15	An exit sign located in the front vestibule above the main double exit doors.	Unknown

The evidence collected during NIST's investigation suggests that the installation of exit signs in the nightclub was consistent, i.e. the signs were the same size and had the same word "EXIT" on them. Although the size of the signs is unclear in the report, the signs should have complied with the USA's Building Construction and Safety Code, i.e. the signs should have had a viewing distance of at least 30.48 metres (100 feet). However, the illumination status of these signs on the night of February 20, 2003 was inconsistent: LSF 10 and LSF 12 were not illuminated; the status of LSF 9 and LSF 15 was unclear; and all the other signs were illuminated.

Three scenarios varying with the illumination status of these signs are examined. In the first scenario, all 7 signs are not illuminated. On the contrary, all signs are illuminated in the second scenario. In the third scenario, the illumination status of the signs is determined according to NIST's report (LSF 9 and LSF 15 which are unclear of illumination status are assumed to be illuminated). In all scenarios, emergency lighting which allows the non-illuminated ext signs to function is assumed to be present throughout.

The coverage area of all 7 exit signs predicted by the signage model (Equation 10.2) described in Section 10.1 is shown in Figure 10.8. Also shown is the percentage of the VCAs covering the entire building in Figure 10.9.

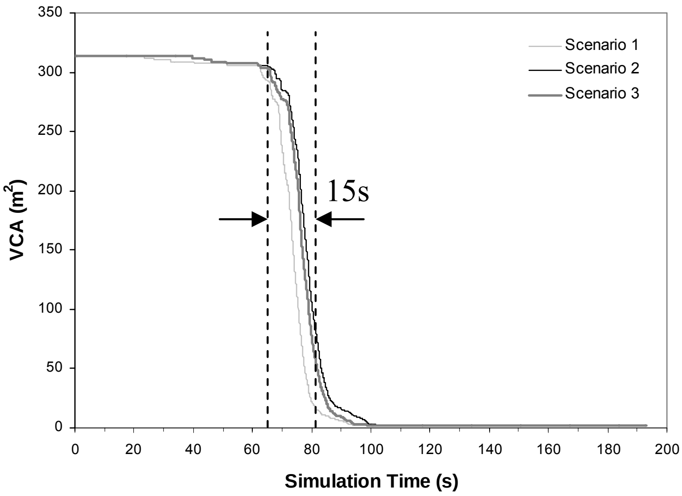


Figure 10.8: The total coverage area of the 7 exit signs.

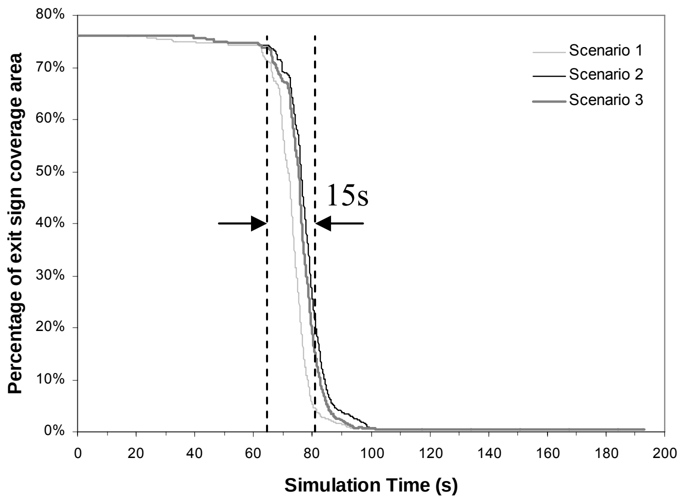
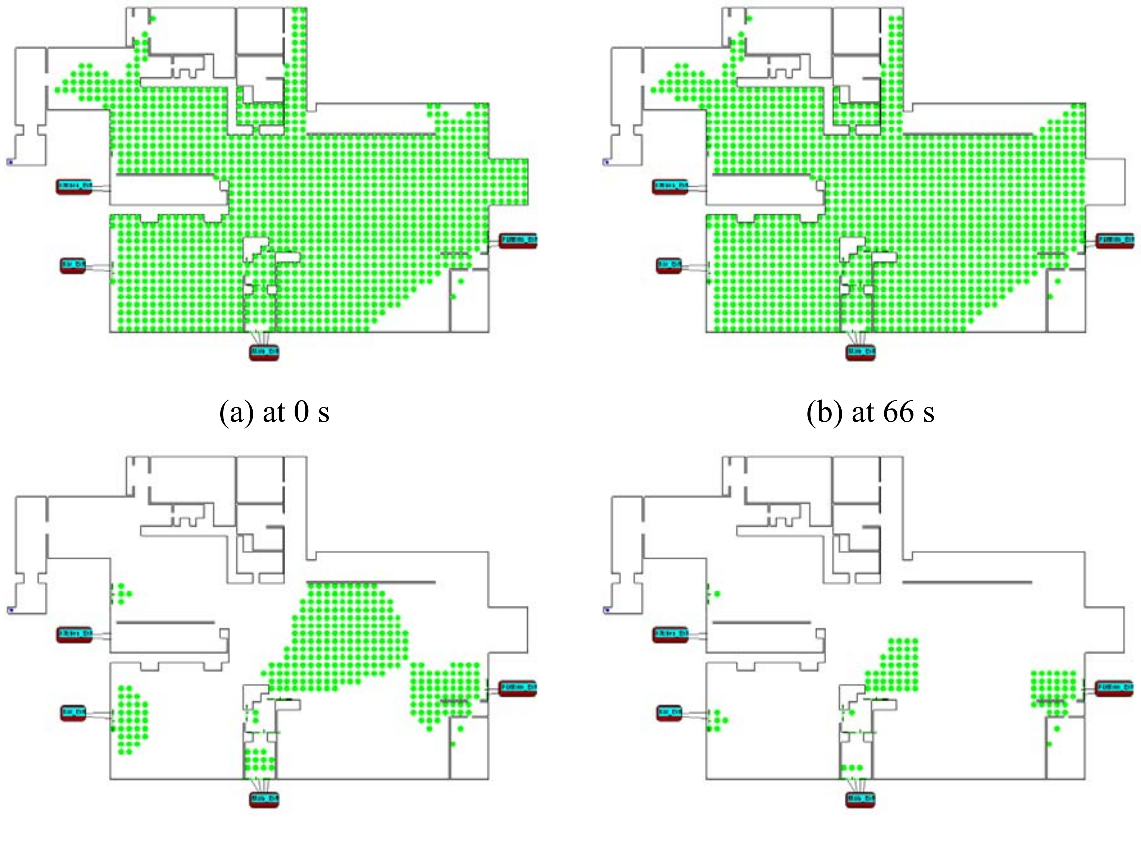


Figure 10.9: The percentage of the VCAs covering the entire building.

Initially, the 7 exit signs cover a total area of 313.5 m^2 which is about 76.1% of the geometry (See Figure 10.10a). During the first period of 66 seconds the coverage area of the exit signs decreases very slowly (See Figure 10.10b). The total VCA continues to cover over 70% of the geometry at the end of this period. Then during the next 15 to 20 seconds the coverage area drops significantly to as low as 5% of the geometry, effectively making all exit signs unable to be used (See Figure 10.10c and Figure 10.10d). The exit signs remain largely obscured till the end of the simulation.



(a) at 0 s (b) at 66 s

(c) at 81 s (d) at 86 s

Figure 10.10: The coverage area of the 7 exit signs at different times in Scenario 3.

It can be seen from Figure 10.8 and Figure 10.9 that the overall variation of the VCAs is similar amongst the three scenarios. However, in scenario 2 the step decrease of coverage area of all light-emitting exit signs is delayed by 5 seconds on average when compared with that of all reflecting exit signs in scenario 1. Similarly, the step decrease of coverage area of the combined light-emitting and reflecting exit signs in scenario 3 is delayed by 3 to 4 seconds on average. The difference is clearer when comparing the VCA of the same sign LSF12 which was located above the platform door. In scenario 2, LSF12 is illuminated; while in scenario 3 LSF12 is non- illuminated according to NIST's report. It can be seen that the decrease of coverage area of the illuminated LSF12 is 5 to 7 seconds later than non- illuminated LSF12 in scenario 3 (See Figure 10.11).

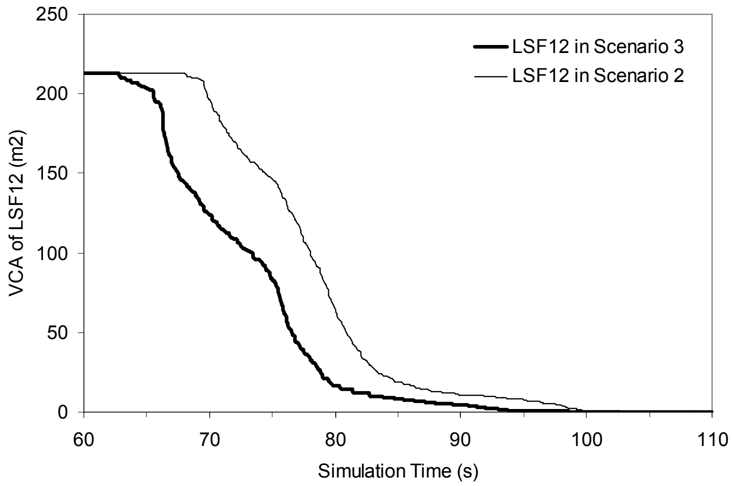


Figure 10.11: The VCA of LSF12 in scenario 2 and 3.

It is apparent that the light-emitting exit signs have a slightly longer period of time to be seen by evacuees than the reflecting signs in such a severe and fast deteriorating condition.

These 3 scenarios are also simulated using the simplified model (Equation 10.3) described at the end of Section 10.1. The results are presented in Figure 10.12 and Figure 10.13. When compared with the results produced by the model using Equation 10.2 (see Figure 10.8 and Figure 10.9), it can be seen that the tendency of these curves is largely identical, yet there are two differences between the two sets of results. The first different appears during the development phase of the fire between 30 s and 60 s. While the curves produced by the model using Equation 10.3 show a step-down of the area of the VCAs, the curves produced by the model using Equation 10.2 show a smoother decrease of the area of the VCAs. The second difference is that the curves produced by Equation 10.2 lag behind those produced by Equation 10.3 about 3 seconds on average. These two differences can be explained by the fact that averaging smoke density in the VCAs during the simulation reduces the level of model prediction accuracy. However, the discrepancy demonstrated in this simulation case is acceptable, so that the simplified model can still be a useful choice to the model user to conduct a quick simulation for analysis.

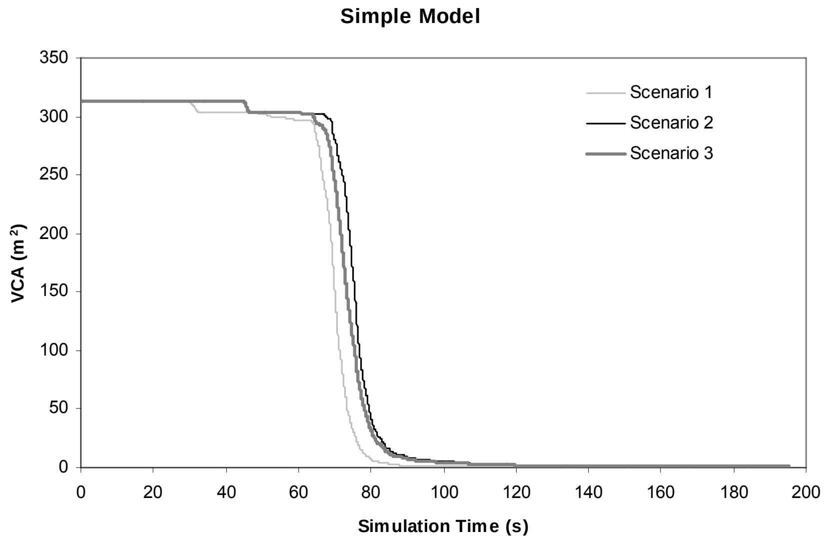


Figure 10.12: The total coverage area of the 7 exit signs (the simplified model).

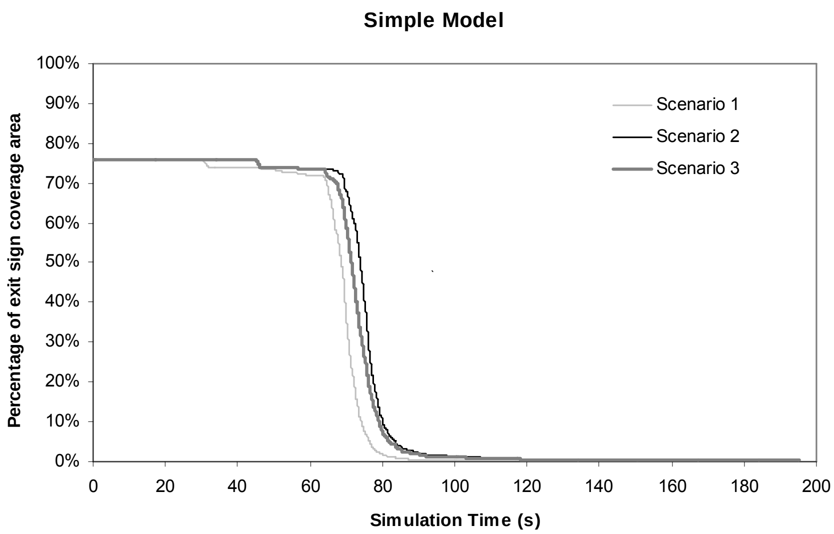


Figure 10.13: The percentage of the VCAs covering the building (the simplified model).

10.3 Summary

One of the threatening conditions during an evacuation from a fire is the visual obscuration effect of smoke. The particles of smoke scatter both the light from the objects and the light from the surrounding environment effectively making them hard to be distinguished from the background or even invisible. Consequently, it can reduce evacuee's capability of wayfinding when the smoke becomes thick enough to obscure exit routes and exit signs indicating exit routes/doors. Therefore, it is important to understand the performance of exit signs in terms of effective covering area during an evacuation from a fire.

This chapter introduced a method which combines Jin's observation data and the VCA sub-model to calculate the decrease of the visibility of exit signs through smoke. In addition, two demonstration cases are described. The first case shows that the visibility of exit signs drops sharply when the smoke density measured by the extinction coefficient increases from zero to 0.5/m. When the smoke density is higher than 0.5/m, exit signs become hardly visible. The light emitting signs perform slightly better in smoke than the reflecting signs. The second demonstration case is based on the reconstruction of a real fire scenario. The case shows that the light emitting signs can function for a few more seconds than the reflecting signs in a fast deteriorating condition. If normal lighting and emergency lighting become unreliable during an evacuation, the light emitting signs are superior to the reflecting signs and may provide wayfinding information to evacuees at crucial moments.

Chapter 11

Occupant Movement and Behaviour in Smoke

In this chapter, the data collected from three sets of experimental trials (see Section 2.3.2, Chapter 2) and that from the SHEBA experiment [Galea *et al.*, 2001] conducted to examine occupant evacuation behaviour and performance in a smoke-filled built environment are analysed. These trials were conducted by four groups of researchers with different objectives. It is noticed, however, that the experimental conditions including the layout of the test systems and the procedures of these trials are similar. Therefore, there is a prospect to merge these data-sets based on comparable or complementary experimental conditions: a single integrated description of the impact of the presence of smoke upon the evacuee is the objective, both in terms of behavioural responses and the direct influence of smoke on the ability of the evacuee to move at the desired travel speed.

11.1 Experimental Research on the Effect of Smoke on People's Egress Performance and Behaviour

Building fires have claimed victims over the years and remain as a major threat to the safety and well-being of building occupants (Section 1.1, Chapter 1). According to the forensic investigation of several major fires in history such as the King's Cross fire in 1987 [Fennell, 1988], the Düsseldorf airport fire in 1996 [Weinspach *et al.*, 1997], the Gothenburg dance hall fire in 1998 [Comeau & Duval, 2000], the Scandinavian Star Disaster in 1990 and the Station Nightclub Fire in 2003 [Grosshandler *et al.*, 2005a], a large proportion of victims were overcome by toxic gases and fire smoke. In addition, many of the survivors were also exposed to harmful gases and smoke during their evacuations. Therefore, in order to assess the required safe-escape time (RSET), it is important to understand occupant evacuation behaviour and performance when travelling through a smoke-filled environment and correctly represent the impact of smoke upon evacuees in modelling an evacuation involving fire hazards.

Four research projects based on controlled experiments using human subjects were conducted by Jin [1978, 1985, 1989, 1997] in Japan, Wright *et al.* [2001b] in the United Kingdom, Frantzich and Nilsson [2004] in Sweden and in Canada using the SHEBA facility [Galea *et al.*, 2001]. These experimental studies attempted to examine the influence of smoke on the ability of the evacuee to move at the desired travel speed and their small-scale behaviour in a smoke-filled built environment. In these experiments non-toxic artificial smoke was generated to fill the test systems, and then the participants were put through the smoke-filled area. The properties of the smoke including the concentrations and irritancy levels were recorded during these trials. The participants' performance data was collected and their behaviour was monitored. Considering the ethical difficulty involved in using human subjects in experiment and evacuation trials that simulate an environment with potential hazards, these four sets of experimental trials provided invaluable data for better understanding people's behaviour and the effect of fire products on people's egress performance.

As the earliest research conducted among the four experiments, Jin's experimental results have been utilised in evacuation models to predict the impact of smoke on simulated agents in evacuation simulation. The Jin 'irritant' curve and 'non-irritant' curve (see Figure 11.1) for instance, are adopted to represent the direct impact of smoke on the ability of the agents to move at the desired travel speed in buildingEXODUS [Galea *et al.*, 2004]. It is expected that with more results obtained from the other experiments model developers will be able to improve the existing model approaches and validate the results produced to better represent the effect and therefore, produce more realistic overall results in evacuation simulation.

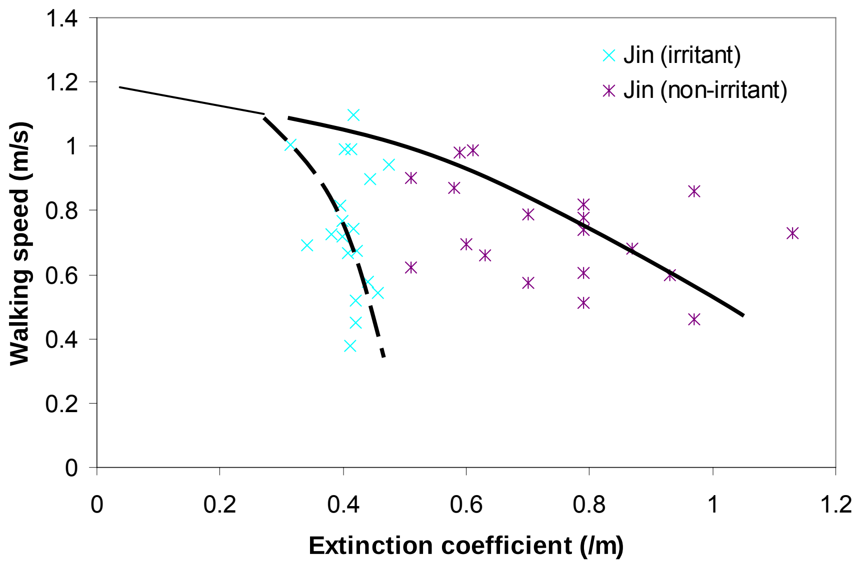


Figure 11.1: The Jin irritant curve and non-irritant curve [Jin 1978, 2008].

It is noticed that the four research groups have different objectives and approaches when examining the effect of smoke on people in their experiments. Firstly, Jin [1978, 1985, 1989, 1997] attempted to simulate a building fire and focused on the effect of smoke on visibility and human behaviour in fire smoke. Frantzich and Nilsson [2004] focused on people's behaviour in seeking for an emergent exit in a tunnel fire. They filled a tunnel with dense smoke and placed several cars in it as a blockage in order to simulate a tunnel fire. Wright *et al.* [2001b] focused on people's interaction with various wayguidance provisions in a smoke-filled building environment. Finally, the SHEBA facility [Galea *et al.*, 2001], which was designed to collect data on human movement and behaviour in a ship, is a representation of a standard corridor found on passenger vessels. Questions are then raised about how to understand the data-sets collected from these experiments and use them to improve the description of the impact of the presence of smoke upon the evacuee in evacuation modelling.

Despite the differences in motivation, the researchers all provided a detailed description of the experimental conditions including the configuration of the test systems, the measurement of smoke density during the trials and the procedures. The comparison of the experiments can be made in two ways. Firstly, if the experimental conditions are comparable between any two experiments, then the data-sets can be used to validate each other. Secondly, if the experimental conditions are not comparable but complementing each other, then the data-sets can potentially be combined to cover a broad range of conditions.

Based on the above consideration, the experimental conditions are examined with an attempt to integrate the results obtained from these experiments in order to improve the original model implemented utilising Jin's data. Compared with the original description of the impact of smoke, this updated model should enable evacuation models to simulate a broader range of environmental conditions in terms of smoke density and occupant behavioural repercussions to exposure to smoke.

11.2 Analysis of the Four Data-sets

11.2.1 Comparison of experimental configurations and conditions

According to the description of the four sets of experiments, they share the following arrangements in common:

- The main part of the test systems was a corridor or a structure similar to a corridor, e.g. a tunnel;

- Smoke was generated to fill the test systems and the smoke density was measured and recorded during the experimental trials;
- Normal lighting was provided in all test systems. Black out and some other lighting conditions/wayguidance systems were also tested in some runs;
- Participants representing the general public were recruited to take part in the experiments without any special selection restrictions;
- Participants were required to navigate through the smoke-filled area without risking themselves by any extreme behaviour, e.g. running along the test system.

Table 11.1 lists the configurations of these experiments in detail. In summary, these experiments simulate a built environment in an emergency situation which requires the participants to navigate a certain distance through a smoke-filled area to escape or to find a safe shelter. The analysis of the impact of smoke upon the participants is then conducted based on their travelling speeds measured and their behaviour observed during the experiments.

Table 11.1: Configurations and conditions of the four experiments.

Research group	Corridor length (m)	Smoke properties	Smoke density in extinction coefficient (1/m)	Number of data / participants
Jin	20	Black, burning woods, kerosene, etc.	0.51~1.13	19
Wright *et al.*	13	Generated from a mineral based fluid, white, and non-toxic.	2.53	18
Frantzich & Nilsson	37	Mixture of polyglycoles, distilled water and acetic acid.	1.93~7.39	32
SHEBA	11	Glycerin ($C_3H_8O_3$), Dipropylene Glycol ($C_6H_{14}O_3$) and Propylene Glycol ($C_3H_8O_2$).	0.0, 0.23, 1.15, 2.30	360

Jin [1978, 1985, 1989, 1997] examined two types of smoke, irritant and non-irritant smoke, and two lighting conditions, with and without a light source. As the other experiments used only non-irritant or less irritant smoke, only Jin's non-irritant data-set is included in the analysis. Jin also mentioned in his report that no significant difference could be identified between the walking speeds measured in the corridor with and without a light source [Jin, 1978]. So no attempt is made to exclude the data collected under black out conditions from Jin's non-irritant data-set.

Wright *et al.* [2001b] measured participants' walking speeds in a corridor filled with smoke while they were aided by six types of lighting systems and wayguidance systems separately. The results are included in the analysis for the similarity in experimental conditions as compared with the other experiments.

Frantzich and Nilsson [2004] simulated a tunnel fire and examined two lighting conditions. They also tested three types of wayguidance systems. Similar to Jin's findings, no significant difference is identified from the results produced in the two lighting conditions combining with the wayguidance systems. Therefore, all of the data collected from Frantzich & Nilsson's experiment is included in the analysis.

Finally, the SHEBA facility simulated more experimental conditions as it was designed to simulate the movement of a ship on the sea. Here only the results produced from the SHEBA experiment conducted under similar conditions to the above three experiments are included in the study, i.e. the facility was steadily fixed at zero degree when the participants passed through the smoke-filled area.

The relative similarity in the experimental configurations and environmental conditions provides the basis for comparing and combining the results produced from these experiments. However, these are still minor differences in the details of the experimental procedures and properties of the smoke used. Further analysis of these differences is carried out in the following sections before the data-sets can be compared and integrated into modelling. Firstly, since irritant effect is not addressed due to insufficient data, the rationality of ignoring the irritant effect in Frantzich and Nilsson's experimental trials is discussed in Section 11.2.1.1. Secondly, in order to quantitatively compare the impact of visual obscuration of smoke upon participant's walking speed, an unimpeded average walking speed is deduced from Jin's data-set in Section 11.2.1.2. Finally, several psychological factors that potentially affected the results obtained from the SHEBA experiment are discussed in Section 11.2.1.3.

11.2.1.1 Irritant Effect

In Jin's experiment [1978, 1985, 1989, 1997], several different materials were burned in order to generate irritant smoke and non-irritant smoke. Jin differentiated the experimental conditions accordingly: using irritant smoke and using non-irritant smoke. He observed clear differences in participants' walking speeds under the two conditions: when the smoke densities were relatively low, the participants' walking speeds observed in both conditions were comparable; when the smoke was relatively thick, the participants walked much slower in irritant smoke than in non-irritant smoke although the smoke densities were still at the same level. Jin [1978, 1997] explained the findings by the irritant effect. As the irritant conditions became severe the participants could not keep their eyes open in the thick irritant smoke and they could only walk in a 'zigzag' manner; whereas the influence of the irritant effect on the participants' walking speed can be ignored when the smoke density is relatively low.

In Frantzich and Nilsson's experiment [2004] the irritant gas was generated by acetic acid under restricted dose control that generally would not affect the participants' health and safety. All participants experienced similar conditions in the tunnel filled by a mixture of smoke and the artificial irritant gas. Considering the facts that (1) the smoke densities measured by extinction coefficient in their experiment (2.0-7.4/m) are much higher than that in Jin's experiments (0.3-1.2/m), (2) the walking speeds measured in their experiment do not decline significantly as expected when taking account of the high smoke density experienced by the participants, but the speeds are more consistent with a hypothetical extension from the end of Jin's non-irritant curve rather than Jin's irritant curve, and (3) there was no explicit complaining about continuous discomfort due to eye irritation in the statement from later interviewing the participants in their experiment [2004], it can then be qualitatively deduced that the irritant effect in Frantzich and Nilsson's experiment is much less severe than that in Jin's experiment using irritant smoke. Therefore, the irritant effect in Frantzich and Nilsson's experiment is ignored in the analysis, and the data-set produced is assumed to be effectively non-irritant, i.e. it can be treated equally with the data-sets produced from the other experiments using non-irritant smoke. It should be emphasised here that both the SHEBA experiment and Wright *et al*.'s experiment used non-irritant artificial smoke.

Although Jin and Frantzich & Nilsson have tried to examine the irritant effect of smoke, there is no adequate measurement to quantitatively compare the irritant effect between the two experiments as well as the effect examined in the other experiments, e.g. the SHEBA experiment and Wright *et al*.'s experiment, which only used non-irritant smoke. Therefore, the analysis of the data mainly focuses on the visual obscuration effect of smoke on participants' walking speeds and behaviour based on the analysis of the results produced from the four experimental studies, and leaves the investigation of the irritant effect to future work when more data regarding the irritant effect is available. Therefore, Jin's irritant data-set is excluded in the comparison with the other data-sets and the irritant effect in Frantzich and Nilsson's experiment is ignored according to the above analysis. The data-sets are then compared on an equivalent basis.

11.2.1.2 Average Unimpeded Walking Speed

In order to compare the data-sets collected from these experiments and evaluate the negative effect of smoke on people's walking speeds, the participants' unimpeded walking speeds are required as the basis in the analysis. However, the unimpeded individual performance data is not available from the experiments conducted by Jin, Wright *et al*. and Frantzich & Nilsson; the information is available to the author from the SHEBA data-set (the SHEBA data-set which involves additional influencing factors is described in Section 11.2.1.3). Given that Jin's data-set has been applied in previous modelling [Galea *et al*., 2004] and that the low end of smoke density measured during Jin's experiment is the lowest among the three experiments (i.e. the effect of smoke on the participants' walking speeds should be the mildest), an attempt is made to estimate the initial unimpeded walking speed from Jin's data-set (i.e. Jin's data-set is extrapolated to determine the speed basis for comparison and evaluation of the negative effect of smoke).

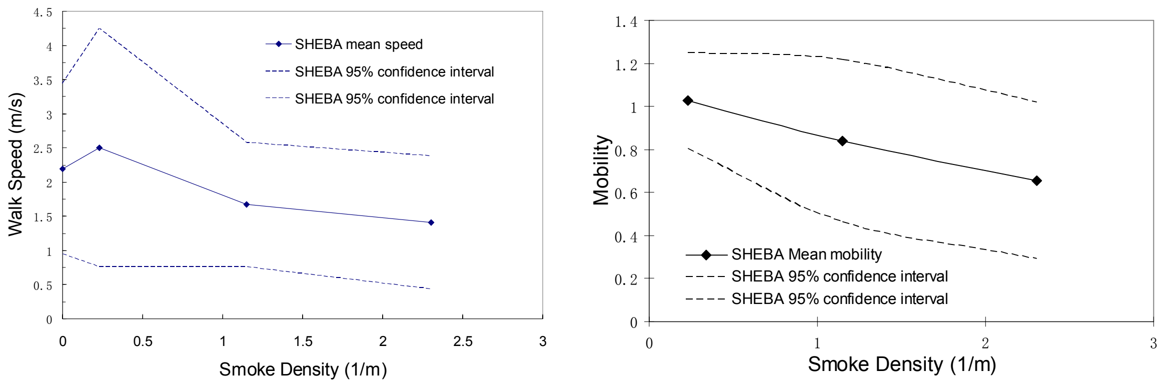
By linearly extending the Jin irritant curve and non-irritant curve to the left side (i.e. from low density smoke to non-smoke conditions, see Figure 11.1), the linear normal unimpeded walking speed obtained measures approximately 1.2 m/s. This speed is also equal to the average fast walking speed in a low density enclosure recommended for calculations involving movement rates [Galea *et al.*, 2004]. Therefore, in the following analysis of the three data-sets, the estimation of the effect of smoke on walking speeds and the calculation of pedestrian mobility are based on the average unimpeded free walking speed of 1.2m/s in a clear environment.

11.2.1.3 The SHEBA data-set

The SHEBA experiment [Galea *et al.*, 2001] provides the most extensive data-set, which includes the performance data of 360 participants: their walking speeds measured in a smoke-filled environment as well as their unimpeded walking speeds in a clear environment (measured when the facility was fixed at zero degree). Also known is the distribution of gender and age of the participant population.

According to the data-set, the participants' average unimpeded walking speed measured in a smoke free environment is 2.2 m/s (see Figure 11.2a). This speed is much higher than the average unimpeded walking speed (1.2 m/s) deduced in Section 11.2.1.2. This discrepancy could be arguably explained by the following factors.

- The SHEBA facility has the shortest travel distance among the four test systems, and the participants were required to walk through the test area twice in each scenario. Therefore, they could become familiar with the layout of the test system easily and gain confidence in performing fast walking. For instance, it is noticed that in the first scenario when no smoke was present the participants were 7.1% faster on average in the second run (2.27 m/s) than in the first run (2.12 m/s).
- The participants were highly motivated to walk fast in response to an assumed emergency situation.
- The participants were asked to perform a straightforward task of going through the test system. No additional task, e.g. looking for an exit sign and exit door, was required during the experiment.



(a) participants' average walking speed

(b) the average speed reduction ratio over the average walking speed measured in non-smoke conditions

Figure 11.2: Average walking speed and mobility curve (the SHEBA experiment). (The dash lines depict the 95% confidence intervals of the data-sets)

In brief, the participants attending the SHEBA experiment were highly motivated, easily gained a good knowledge of the environment and were required to perform a relatively easier task compared with the participants attending the other three experiments. In order to be able to compare with the results produced from the other experiments, the participants' walking speeds measured in smoke during the SHEBA experiment are firstly converted to reduction ratio (i.e. the mobility) over the average walking speed measured in the smoke free environment (see Figure 11.2b and Table 11.2), as the mobility represents the relative effect of smoke upon the participants' walking speeds.

Table 11.2: The average mobility measured in the SHEBA experiment

Scenario Number	**1**	**2**	**3**	**4**
Smoke density in extinction coefficient (1/m)	0	0.23	1.15	2.30
Number of data points	354	115	127	100
Measured mean walking speed (m/s)	2.19	2.50	1.67	1.41
Mean mobility	1.00	1.03	0.84	0.66
95% confidence intervals of the SHEBA data-set after being converted to mobility	NA	0.80~1.25	0.46~1.22	0.29~1.02

11.2.2 Data Description and Analysis

Based on the above introduction of the four experiments and the analysis of the experimental configurations and conditions, it can be seen that the experiments conducted by Jin and Frantzich & Nilsson cover the most extensive smoke density ranging almost successively from 0.5/m to 7.39/m; and more importantly they provide comparable scenarios of participants navigating in smoke-filled environments. Therefore, the data-sets produced from these two sets of trials are selected to produce an integrated and continuous representation of the direct influence of smoke on the ability of the evacuee to move at the desired travel speed.

The experiments conducted by Wright *et al.* and the SHEBA project measured the participants' performance at several discrete levels of smoke density, and moreover, the running of the SHEBA experiment was influenced by additional factors and produced highly motivated egress behaviour. Therefore, the results produced from these two experiments are then only used for validation and comparison with the new representation of the impact of smoke deduced from the experiments conducted by Frantzich & Nilsson and Jin.

Jin's non-irritant data-set (represented as a '×') and the non-irritant curve (represented as the thick curve) derived from the data-set are shown in Figure 11.3. The non-irritant curve predicts the reduction of people's walking speeds from an initial speed of 1.2m/s to approximately half of that as the smoke density increased from about 0.2/m to 1.0/m. Due to the lack of published data concerning people's walking speed when the smoke density is higher than 1.0/m, previously it was assumed that evacuees start crawling or remain at the same speed in thicker smoke.

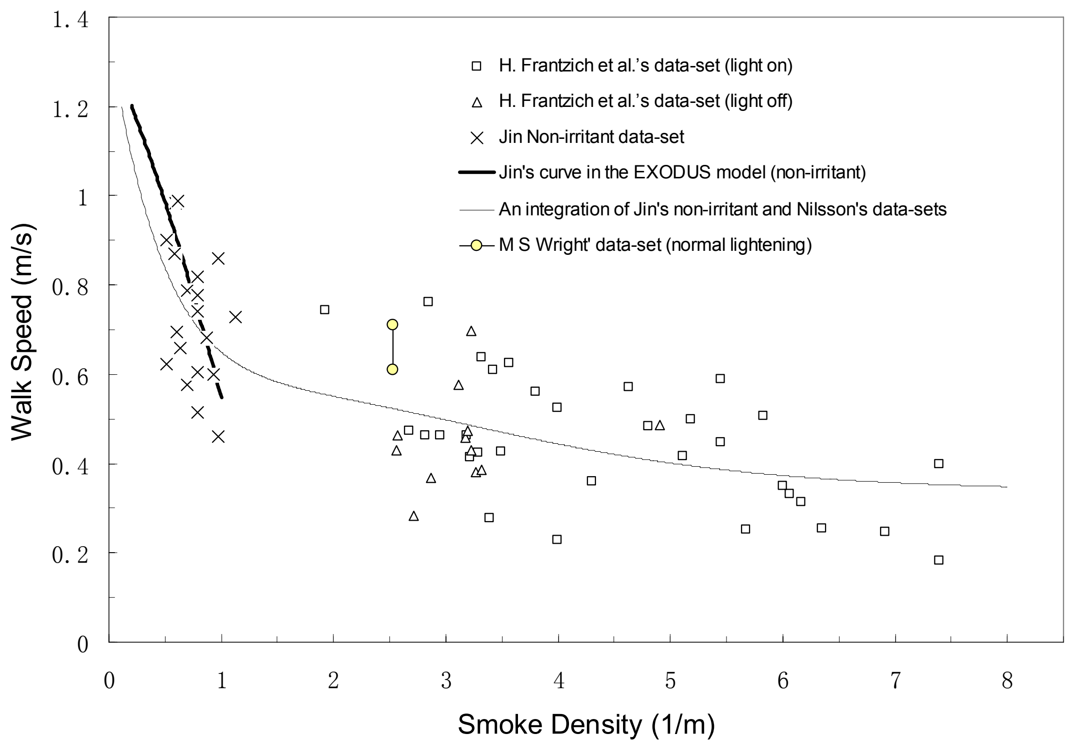


Figure 11.3: Walking speeds measured in the experimental trials.

Frantzich & Nilsson's data-set (represented as a '□' and a 'Δ' in Figure 11.3) 'connects' Jin's non-irritant data-set at the smoke density of 2.0/m and largely extends the range of smoke density up to about 8.0/m. The data-set depicts the impact of much thicker smoke upon the participants' walking speeds during the trials. It can be seen that the walking speeds continuously decline with further increasing of smoke density, and then the speeds plateau, representing relatively stable performance beyond a certain threshold value.

In order to produce an integrated representation of the effect of smoke in evacuation modelling, a new curve represented as the thin smooth curve in Figure 11.3 is produced through curve fitting using both Jin's non-irritant data-set and Frantzich & Nilsson's data-set. This curve shows the decline of walking speed due to the negative effect of smoke as the smoke density increases from 0.2/m to 8.0/m. It can be seen that the new curve is consistent with the Jin 'Non-Irritant' curve within its applicable range, while it extends the range of smoke density to about 8.0/m.

The new curve can be treated as two successive segments according to the gradient: a curve with a steep gradient covering the smoke density ranging from 0.2/m to 1.5/m; and a curve with a reduced gradient covering the smoke density from 1.5/m up to 8.0/m. This division shows a notable difference in the impact of smoke and the visual obscuration effect on people's walking speed. Accordingly, a hypothetical behavioural model is presented in Section 11.3.4 trying to explain the difference through observed participant's behaviour. However, more observational evidence and further investigation are required to validate this model.

Jin [1978, 1997, 2008] reported that at low visibility the participants' behaviour was similar to that found in darkness, i.e. they walked along the wall in the corridor and kept touching it to maintain their orientation. Similarly in irritant smoke the participants could not keep their eyes open and walk accurately. Besides, they were forced to walk along the wall too. Such behaviour of the participants touching and following walls while moving was also observed by Frantzich and Nilsson [2004] during their experimental trials: about 80% of the walking paths followed the walls and 63% of the participants did not leave the wall after they followed it. The analysis based on the interviews of the participants also revealed that the participants intended to find a wall that they could follow rather than happening upon a wall at the beginning that they then followed. Frantzich and Nilsson explained the behaviour by the fact that the participants used tactile perception to a greater extent than visual perception to navigate and find emergency exits when the visibility condition deteriorated below a certain level [2004].

The participants' behaviour obviously influenced their walking speeds attained. From the smoke density of 0.2/m to 1.5/m, i.e. the range mainly examined by Jin, the visibility condition continuously deteriorated along with an increase of smoke density; while the participants were still able to use visual perception to navigate and move. But as the smoke density increased, the walking speeds decreased almost linearly as the first segment of the new curve shows in Figure 11.3. When the smoke density went higher than 1.5/m, i.e. the range of smoke density mainly examined by Frantzich and Nilsson, the participants could barely use visual perception to navigate any longer, but depended more on tactile perception. This was proved by the high proportion of walking paths along the walls observed during the experiment as well as the similar behaviour observed at low visibility in Jin's experiment. Therefore, the walking speeds measured in Frantzich & Nilsson's experiment in a dense smoke-filled environment represent people's evacuation performance assisted by tactile perception. Since people's navigation behaviour by touch would not be affected much by further increasing the smoke density as visual perception, walking speeds observed in smoke density of 1.5/m and above is represented by the second segment of the new curve which plateaus with a reduced gradient shown in Figure 11.3.

Wright *et al.*'s data-set (represented as a '○') lies right above the new curve and within the range of Frantzich & Nilsson's data-set dispersed around the new curve in Figure 11.3, showing that it is also consistent with the other data-sets. The importance of Wright *et al.*'s experiment is that they tested the impact of several wayguidance systems upon people's walking speed in smoke in comparison with the impact of the overhead emergency lighting and the normal lighting. The results [Wright *et al.*, 2001b] show that in a smoke-filled environment (the smoke density measured 2.53/m) the participants performed twice as better in the scenarios when they were aided by the electroluminescent wayguidance system, the LED wayguidance system and the miniature incandescent wayguidance system than in the scenarios when they were aided by the overhead emergency lighting and the normal lighting. However, as no more tests have been performed at other levels of smoke density, the improvement of walking speed in a smoke-filled environment can only be qualitatively suggested here.

11.3 The Application of Experimental Results in Evacuation Modelling

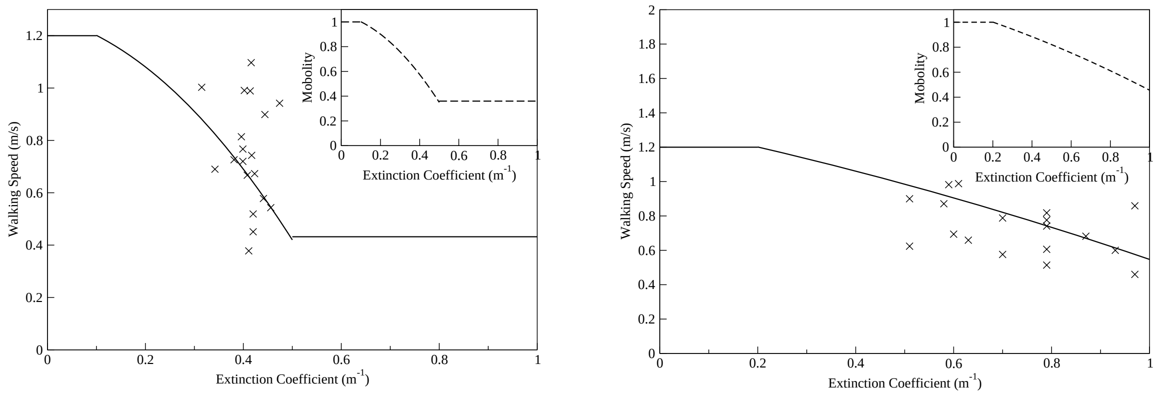
The impact of non-irritant smoke on people's walking speed is a reflection of reduced visibility due to the visual obscuration effect of smoke. In contrast to walking in a clear environment, people travelling in smoke have to slow down to discern the layout of building and identify building components such as free spaces, walls, doors, stairway and obstacles etc., and more importantly avoiding collision. Smoke and the consequent effect of reduced visibility could also influence people's response and evacuation behaviour [Proulx and Fahy, 2008]. For instance, people may try to avoid inhalation of smoke by redirecting to other available exits [Gwynne *et al.*, 2001].

In buildingEXODUS, the impact of smoke on people's physical ability is simulated by the manipulation of the Mobility attribute [Galea *et al.*, 2004]. Mobility is a multiplicative factor used in conjunction with the Travel Speed and Agility attributes. It represents a uniform description of the impact of smoke upon people's walking speed regardless of people's gender, age and the other attributes. The calculation of mobility due to the influence of smoke is based on the results produced from experimental trials, e.g. Jin's experiment using human subjects.

The subjects' behaviour observed during the trials is also represented in the implementation of the behaviour sub model in buildingEXODUS [Section 2.3.11.2 in Galea *et al*., 2004].

11.3.1 The application of Jin's data-set in buildingEXODUS

Jin's data-set [1978, 2008] as an estimate of the irritant and non-irritant effect of smoke on human subjects has been introduced into buildingEXODUS to represent the impact of exposure to irritant and non-irritant smoke on an evacuee's walking speed. In particular, two curves labelled the Jin 'Irritant' curve (see Figure 11.4a) and the Jin 'Non-Irritant' curve (see Figure 11.4b) are derived from Jin's data-set and used in the corresponding situations [Section 2.3.10 in Galea *et al*., 2004].



(a) The Jin 'Irritant' curve and walking speeds measured in the experiments (×).

(b) The Jin 'Non-Irritant' curve and walking speeds measured in the experiments (×).

Figure 11.4: (a) The Jin 'Irritant' curve and (b) the Jin 'Non-Irritant' curve. (The initial unimpeded travel speed is set to 1.2m/s. The inserts in the two figures show the corresponding mobility curves.)

Firstly, if the irritant toxins in the environment are not modelled explicitly, a simplified approach is adopted to represent the impact of both visual obscuration and the irritancy in general. Here the Jin 'Irritant' curve is utilised, based on Jin's experiment, where the irritants were present, although not outlined in detail. The mobility attribute is kept constant up to the value of 0.1/m after which it is calculated by

$$Mobility = -2.08K^2 - 0.38K + 1.06, \qquad \textbf{(Equation 11.1)}$$

obtained through curve fitting, where K represents the extinction coefficient of smoke. For smoke concentrations above 0.5/m, evacuees are assumed to have a constant mobility of 0.36 or a travel speed equivalent to the *Crawl Rate*, i.e. 20% of the occupant's fast walking speed (see the insert in Figure 11.4a).

Secondly, if the concentrations of irritant gases are available for modelling, i.e. the engineer has sufficient data describing the levels of irritant gases during the scenario in question, the Jin 'Non-Irritant' curve which determines the visual obscuration effect of the smoke is utilised. The mobility attribute is equal to 1.0 up to the concentration of 0.2/m; between the concentrations of 0.2/m and 1.0/m, the mobility is determined by

$$Mobility = -0.161K^2 - 0.488K + 1.105, \quad \textbf{(Equation 11.2)}$$

obtained through curve fitting too; above the concentration of 1.0/m the travel speed is set to the *Crawl Rate* or the mobility attribute is kept constant if the crawl option is disabled (see the insert in Figure 11.4b). In the mean time, the irritant effect of smoke is represented through the FED model derived from Purser's work [1995, 2001, 2008]. The most effective impact of the upper two factors is then selected to represent the reduction of evacuees' travel speeds.

In the buildingEXODUS model not only was Jin's data-set used to determine the impact of smoke on evacuees' mobility, but the specific behaviour observed by Jin was also modelled. In the experiment, Jin [1978] observed that the participants could hardly maintain the straight walking behaviour in the smoke-filled corridor and sometimes lean on the wall to make progress. This behaviour became more apparent in dense and/or irritant smoke.

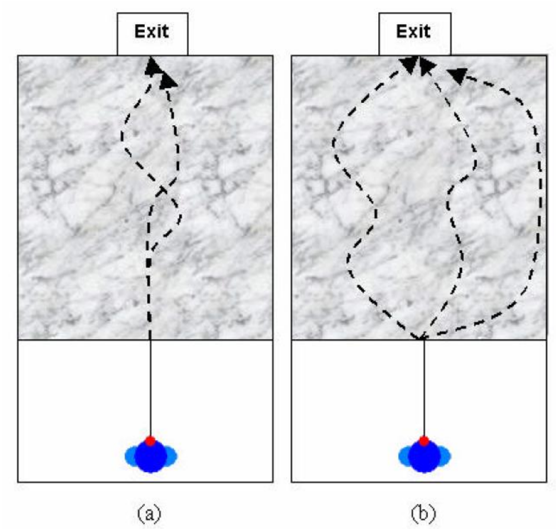


Figure 11.5:Non-optimal routes adopted by evacuee travelling in smoke-filled area.

This type of behaviour observed when the participants walked in a smoke-filled environment has been modelled in the buildingEXODUS model as the *Smoke Stagger* option [Section 2.3.11.2 in Galea *et al*., 2004]. When the option is enabled, an evacuee's route adoption will be affected by the presence of smoke. A disturbing effect on the attractiveness of nodes, which results in a non-optimal route followed by evacuees in a smoke-filled area space (see Figure 11.5a), is introduced to represent the influence. The higher the smoke density, the stronger the disturbing effect will be. In addition, when evacuees reach any boundary, e.g. a wall, they are more likely to stick on walking along it rather than staggering back to open space (see Figure 11.5b).

It should be pointed out that the evacuees' behavioural response to the presence of smoke implemented in the buildingEXODUS model and the participants' behaviour observed in the experiments performed by Jin [1978] and Frantzich & Nilsson [2004] are different in the following two aspects.

Firstly, two types of behavioural responses observed in Jin's experiment are implemented in the buildingEXODUS model. They are the *Smoke Stagger* behaviour and the tendency to use walls as a navigation aid. In the model, when evacuees encounter smoke they have the option to demonstrate the non-optimal path adoption behaviour within a certain range of smoke density (between 0.1/m and 0.5/m measured by extinction coefficients). This behaviour is implemented by biasing the attractiveness of the nodes in evacuee's desired travel direction. In addition to the staggering behaviour, when evacuees happen to reach edge or wall nodes that are closer to their target, they are more likely to follow these nodes. The *Smoke Stagger* behaviour depends on the smoke density and expresses certain degrees of randomicity; the behaviour of *walking along walls* depends on the geometry configuration and is also linked to the *Smoke Stagger* behaviour. Therefore, no purposive movement towards walls is represented in the current model.

Frantzich and Nilsson [2004] found, under experimental conditions, that the participants did try to find a wall and use it as an aid when navigating in the smoke-filled tunnel and they would like to stick to the behaviour of following walls until an exit was found. It can be seen that the attempt to use walls is an intuitive behaviour. If evacuees have less knowledge of the building structure, finding a wall can be a stochastic process, e.g. the *Smoke Stagger* behaviour; whilst it is a purposive movement if evacuees have some knowledge of the structure or if they can predict the structure based on their experiences. For instance, in Frantzich & Nilsson's experimental trials, the participants moved straight toward the walls and were reluctant to stagger back to open spaces, as they can easily imagine the layout of the road tunnel, although they had no experiences of the tunnel prior to the trials.

Secondly, in buildingEXODUS when the smoke density exceeds 0.5/m in irritant smoke or 1.0/m in non-irritant smoke, the model assumes that evacuees are forced to crawl or they travel at a speed which is comparable to the speed of crawling (a combination of the irritant effect and the visual obscuration effect is also considered to determine the threshold value for switching to the crawling behaviour). A crawl rate, an arbitrary 20% of fast walking speed, is then employed to determine evacuees' travel speeds. The rationality behind the option of crawling is that crawling low is generally considered as an expected emergency response for evacuees in a smoke-filled environment, as cleaner and cooler air is near the floor whilst hot smoke rises to the ceiling. However, the crawling behaviour was not observed under experimental conditions during any of the four experimental trials at all smoke density levels. Instead, the wall-following behaviour was reported by Jin [1978], and was more evidently observed in the trials with dense smoke conducted by Frantzich and Nilsson [2004]. Therefore, the second behaviour should be taken into account in representing the impact of smoke, especially where wall easily accessible is present.

In summary, Jin examined the smoke concentrations approximately between 0.3/m to 1.2/m; the modelling of human behaviour and performance in smoke with the concentrations beyond this range had to be based on assumptions due to a lack of published data and observation evidence previously. It then raises the requirement to refine and validate the current implementation when more results are available from other comparable experimental research [Frantzich & Nilsson, 2004, Wright *et al.*, 2001b, Galea *et al.*, 2001].

11.3.2 The New Mobility Curve

Based on the analysis of the four data-sets in Section 11.2.2, an attempt has been made to integrate the data collected from the experimental trials conducted by Jin [1978, 2008] and Frantzich & Nilsson [2004] to product a single integrated description of the impact of the presence of smoke upon the evacuee.

Firstly, a new speed curve is produced by integrating the two data-sets (see Figure 11.3). The Jin's non-irritant curve and irritant curve were previously obtained by finding a best fit of Jin's non-irritant data-set to a quadratic equation ($y = a_0 + a_1 t + a_2 t^2$). However, it is noticed that not only is a combination of Jin's non-irritant data-set and Frantzich & Nilsson's data-set nonlinear, but the two data-sets also have different tendencies: the speeds in Jin's non-irritant data-set reduce more quickly than Frantzich & Nilsson's data-set with the increasing of smoke density (see Figure 11.3). Therefore, an exponential equation potentially fits the two data-sets better than a quadratic equation. The new speed curve (Equation 11.4) is then obtained by finding a best fit of the two data-sets to the exponential Equation 11.3.

$$y = a_0 + a_1 e^{-t} + a_2 t \cdot e^{-t} + a_3 t^2 \cdot e^{-t} \qquad \textbf{(Equation 11.3)}$$

This nonlinear least-squares (NLLS) problem is solved by the Levenberg-Marquardt algorithm [Levenberg, 1944; Marquardt, 1963]. This curve (see Figure 11.3) depicts the average walking speed achieved by participants in the test systems filled with non-irritant smoke.

$$Speed = 0.34 + 1.02e^{-K} - 0.63K \cdot e^{-K} + 0.45K^2 \cdot e^{-K} \text{ (m/s)} \qquad \textbf{(Equation 11.4)}$$

(K represents the extinction coefficient (1/m) of the smoke.)

Secondly, the new speed curve (Equation 11.4) is converted into a mobility curve. Mobility represents the deviation of evacuees' capability from their initial unimpeded status under certain conditions. The conditions may include physical disability, the influence of visual obscuration and the impact of exposure to toxic and irritant gases and smoke. Given the new speed curve and the unimpeded initial walking speed of 1.2m/s deduced in Section 11.2.1.2, the relationship between the mobility and the smoke density can be expressed by

$$Mobility = \frac{0.34 + 1.02e^{-K} - 0.63K \cdot e^{-K} + 0.45K^2 \cdot e^{-K}}{1.2}. \qquad \textbf{(Equation 11.5)}$$

The Jin 'Non-Irritant' curve defines the reduction applied to evacuees' walking speeds when travelling through a smoke-filled area with a measured extinction coefficient ranging from 0/m to 1.0/m. The new mobility curve is consistent with the Jin 'Non-Irritant' curve within this range as it is derived from the combination of Jin's non-irritant data-set and Frantzich & Nilsson's data-set; and more importantly, the new mobility curve extends the applicable range of smoke density up to 8.0/m since it includes the data-set collected from the experimental trials using relatively thick smoke.

The Jin 'Non-irritant' curve has been successfully used in the buildingEXODUS model to determine the visual obscuration effect of smoke on evacuee's mobility. The new mobility curve can be used to determine the impact of smoke obscuration upon people's mobility when the smoke density is explicitly specified, especially when the smoke density is high or varies within a broad range, and the behavioural tendency to move along walls is represented.

11.3.3 Comparison of the SHEBA Data-set with the New Mobility Curve

Equation 11.5 does not take the SHEBA data-set and Wright *et al.*'s data-set into account. The reason the SHEBA data-set was excluded is that the participants in the SHEBA experiment were obviously affected by additional psychological factors as discussed in Section 11.2.1.3. The SHEBA data-set is then used to estimate the impact of the psychological factors upon the participants. Also Wright *et al.* examined a single smoke density during the trials; the speed measured only varies with the lighting systems and wayguidance systems tested. In contrast, the experimental trials conducted by Jin and Frantzich & Nilsson's are closer to the objective here, i.e. examining the visual obscuration effect of smoke upon evacuee's walking speed in a continuous range of smoke concentrations. The SHEBA data-set and Wright *et al.*'s data-set are used to compare with the new mobility curve and validate the new curve to some extent.

The SHEBA data-set shows that 115 out of the 360 participants attended both of the first two scenarios, i.e. travelling through the test system in clear air and in smoke of low density (0.23/m). Their average travelling speed measured in the second scenario with smoke is 2.5m/s. This speed is a little higher than the average travelling speed of 2.4 m/s measured in the first scenario without smoke (see Figure 11.2a). Further investigation shows that despite the presence of smoke in the second scenario, 57.4% of the 115 participants raised their travelling speed by 10 percent on average compared with their speeds in the first scenario where no smoke was present. The increase of travelling speed in smoke reveals an important behaviour that has not been observed in the other experiments: when people were faced with a environment filled with mild smoke and the smoke density has not increased to a level that can effectively reduce people's visibility, they tend to 'rush' as a stimulated response to the perception of smoke, i.e. they are motivated by the presence of (even) non-irritant smoke. The results produced in the SHEBA experiment also show that the motivation also had an impact on the participants' performance when the smoke density was increased further.

In contrast to the participants in the other experiments, the participants in the SHEBA experiment (1) were highly motivated by initial contact with smoke to walk faster than their unimpeded fast walking speed; (2) they were required to perform a straightforward task of passing through the SHEBA facility with and without smoke; and 3) they could become well familiar with structure of the SHEBA facility during the trials (every participant performed the trials twice). All these factors contribute to the overall higher performance in terms of travelling speeds as compared with the data-sets obtained from the other experiments at several comparable levels of smoke density. Therefore, the comparison of the negative effect of smoke on the participants' ability to walk at desired speeds between the SHEBA experiment and the other experiments is based on the mobility, i.e. the relative speed reduction rate rather than the walking speeds measured.

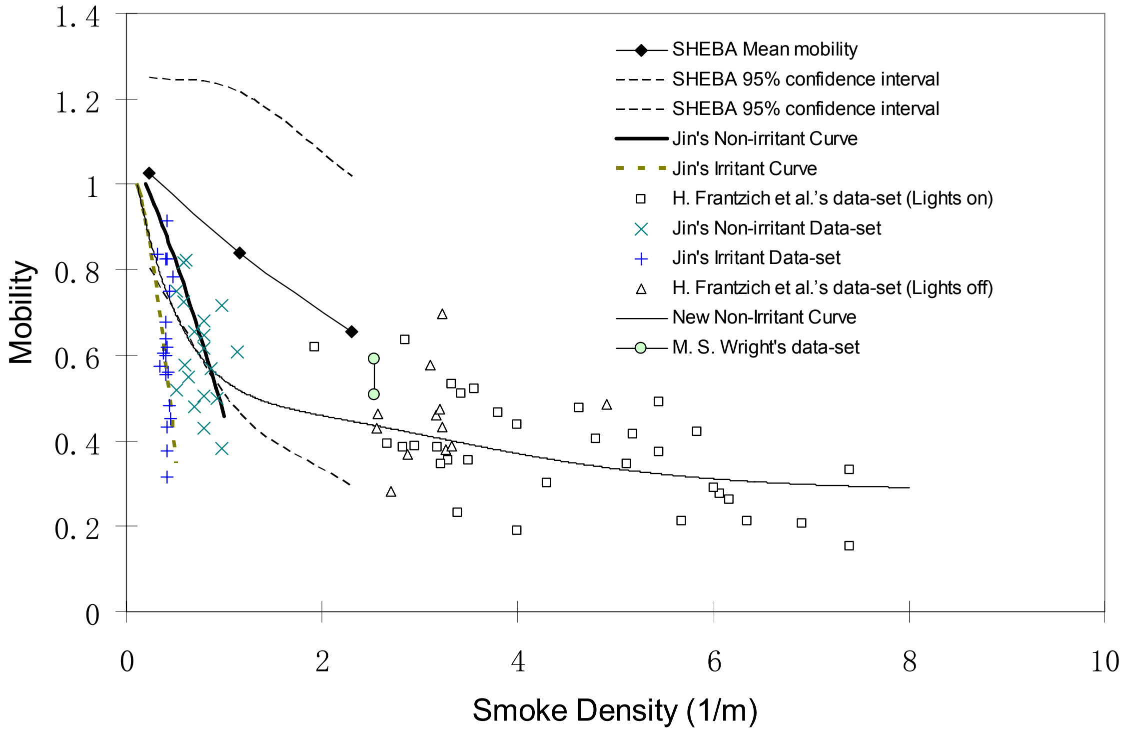


Figure 11.6: The new mobility curve and the four data-sets converted to mobility.

The SHEBA data-set (mean mobility represented as a '♦') and its 95% confidence intervals (represented as the dashed lines) are shown in Figure 11.6 together with the original Jin's non-irritant curve and the new non-irritant mobility curve (represented as the thin curve). Also shown are Jin's non-irritant data-set (represented as a '×'), Frantzich & Nilsson's data-set (represented as a '□' and a 'Δ') and Wright *et al.*'s data-set ('○'), which have been converted to the values of mobility.

It is apparent from Figure 11.6 that with the increase of the smoke concentrations from 0.23/m to 1.0/m the original Jin's non-irritant curve predicts that the mobility decreases from 0.98 to 0.46 (this value is estimated at a smoke density of 1.0/m; the original model also assumes the mobility to be a constant, i.e. 0.46, irrespective of further increasing the smoke density); while the new mobility curve predicts that the mobility decreases from 0.88 at a smoke density of 0.23/m to 0.54 at a smoke density of 1.0/m, and it drops further to 0.45 at a smoke density of 2.3/m. Both of the two curves predict a steep decrease of mobility between 0.23/m and 1.0/m;

beyond the smoke density of 1/m the original model assumes that people have a constant mobility of 0.46 or they travel at a speed equal to the crawl rate, while the new mobility curve predicts a further, though very small, decrease in mobility with the increase of the smoke density. It can be seen that the new mobility curve is mostly consistent with the Jin's non-irritant curve in the range of smoke density examined above.

In the same range of smoke density the SHEBA mobility curve decreases from 1.03 at a smoke density of 0.23/m to 0.66 at a smoke density of 2.3/m. However, the SHEBA curve apparently differs from the upper two curves: not only does the SHEBA curve have an initial value higher than 1.0 at a smoke density of 0.23/m (i.e. the participants walked faster in moderate smoke than they did in a smoke free environment), but it also has a much smaller gradient than the other two curves. It is apparent that the visual obscuration effect of smoke upon the participants' walking speeds in the SHEBA experiment are diminished by other factors, e.g. being motivated by initial contact with smoke. When the smoke density becomes higher, i.e. the smoke density is 1.0/m and above, the 95% confidence intervals of the SHEBA data-set tend to overlap Frantzich & Nilsson's data-set along the new non-irritant curve. The difference between the new non-irritant curve and the mean mobility curve of the SHEBA data-set is then diminished.

It can be seen that the impact of the psychological factors upon the participants during the SHEBA experiment results in higher walking speeds and a smaller speed reduction rate with the increase of the smoke density in comparison with the results obtained from Jin's experiment. This 'reversed' impact of smoke upon the participants' walking speeds takes effect mostly when the visual obscuration effect of smoke was moderate in the trials, i.e. the smoke density was within the range which was measured mostly during the SHEBA experiment and Jin's experiment. The 'reversed' impact becomes less influential when the visual obscuration effect of smoke increases to a certain degree, i.e. the smoke density reached the highest level tested in the SHEBA experiment and the range examined in Frantzich & Nilsson's experiment.

The findings based on the SHEBA data-set confirmed the two stages of the effect of smoke upon people's walking speed presented by Jin's data-set and Frantzich & Nilsson's data-set. The large-scale tests performed in the SHEBA facility provide extra credibility to the new non-irritant curve.

11.3.4 Behavioural Model Determining People's Performance and Behaviour in Smoked Filled Environment

In Section 11.3.1 and Section 11.3.2, the approach of modelling the impact of smoke determines the occupant's walking speed in a smoke-filled environment according to the empirical data obtained from experimental drills or observation. And it relates the reduction of travel speed to the properties of smoke, such as the level of irritant and density. For instance, buildingEXODUS utilised the Jin 'Irritant' curve (see Figure 11.4a) and the Jin 'Non-Irritant' curve (see Figure 11.4b) obtained from Jin's experimental trials. The accuracy of this approach is often restricted to the configuration of the experiment and the specific subject population attending the experiment. The compatibility of the data when applied to another population and scenario is therefore in question. For example, although the range of smoke density examined in Jin's experiment and the SHEBA experiment mostly overlap, Jin's Non-irritant curve could not explain the overall higher performance and the unusual increasing of travelling speeds observed at a low level of smoke density as compared with the speeds observed in a smoke free environment during the SHEBA experiment. In another example, the gradient of Jin's Non-irritant curve is inconsistent with (larger than) that derived from Frantzich & Nilsson's data-set measured in a higher level of smoke density. Therefore, the original Jin's Non-irritant curve could not be automatically extrapolated to predict people's travel speeds when the smoke density increases further, but other behavioural factors must be taken into account to integrate the results produced from the two experiments.

Alternatively, it has been noticed that the participants' behaviour was influenced by the presence of smoke, and they demonstrated consistent patterns of behaviour in these experimental trials:

- both the SHEBA experiment and Jin's experiment demonstrated a similar speed reduction trend among the participants at the smoke density ranging between 0.2/m and 1.5/m due to the visual obscuration effect;
- the participants were observed walking along the walls when the smoke density increased further in the experiments conducted by Jin and Frantzich & Nilsson; while the lower end of Jin's Non-irritant data-set is comparable to the high end of Frantzich & Nilsson's data-set within the joint range of smoke density between 1.0/m and 2.0/m;
- when further increasing the smoke density to a significant level (the smoke density mostly tested by Frantzich & Nilsson), the participants were still able to achieve certain speeds in making progress in dense smoke by following the walls, rather than becoming unable to move.

It can be seen that the presence of smoke obviously affects the participants' behaviour. With the increase of smoke density, the pattern of behaviour changes too, while the travel speeds that the participants can achieve are related to the pattern of behaviour demonstrated within the corresponding range of smoke density. Thus, an alternative approach of modelling people's performance and behaviour in smoke is described in this section. This approach focuses on people's common behaviour observed in a smoke-filled environment and links the performance data (in terms of the travel speeds) collected in the experimental trials with the pattern of behaviour.

According to the analysis of the four experiments in Section 11.3.3 which examined the participants' egress performance and behaviour in a similar geometry configuration at different levels of smoke density, there are three forms of behavioural repercussions corresponding to three levels of smoke density.

Initially, when the smoke density is relatively low, the presence of smoke strengthens people's perception of the state of emergency, i.e. people are motivated to escape from the smoke quickly. This results in people 'rushing' within a modest acceleration in their movement which could be faster than their walking speeds observed in normal situations; i.e. the psychological motivation is more influential than the physiological impediment provided by the environment [Jin, 1978, 2008]. This type of 'rushing' behaviour was mostly observed in and supported by the SHEBA experiment at a mild smoke density around 0.23/m.

Then with further increasing of the smoke density the visual obscuration due to the presence of smoke begins to take effect. According to Jin's estimation of the visibility in smoke though trials, people's visibility decreases almost linearly with increasing of the smoke density. In the mean time, people's travelling speed also decreases with decreasing of visibility. People may still want to travel as quickly as possible in smoke, but the psychological motivation becomes less influential than the physiological impediment provided by the environment; and the higher the smoke density, the more influential is the physiological impediment. This stage is approximately covered by the smoke density examined by Jin's experiment and the middle range of the smoke density examined by the SHEBA experiment. It characterises the visual obscuration effect of smoke which can be expressed by a (almost linear) decrease of walking speed.

Finally, the smoke density increases to a level which is high enough to prevent people from using visual perception to make progress. As a result, people have to mostly rely on their perception of touch to navigate. Therefore, this stage represents people's behaviour and performance that is similar to that can be found in a darkness situation; i.e. the psychological motivation is again less influential than the physiological impediment provided by the environment, but that while the environmental conditions worsen, the impact upon the individual remains approximately constant. The typical behaviour at this stage includes seeking support (e.g. walls), movement by touch and crawling previously assumed in buildingEXODUS [Galea *et al.*, 2005]. This stage is represented by the highest level of smoke density examined in Jin's experiment [1978] and the SHEBA experiment [Galea *et al.*, 2004], and most of all, Frantzich & Nilsson's experiment [2004].

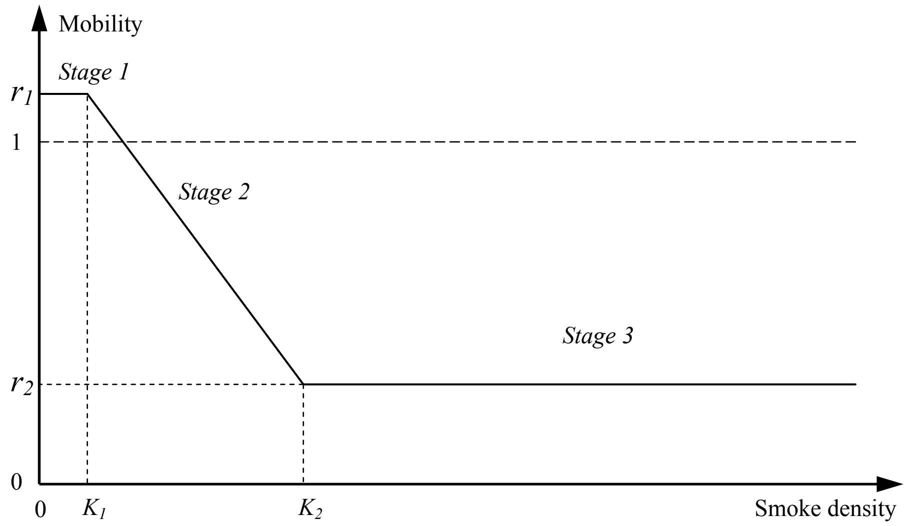


Figure 11.7: Mobility corresponding to behavioural responses at three levels of smoke density.

The mobility corresponding to the three types of behavioural response to the smoke density is shown in Figure 11.7. Stage 1 represents people's behaviour in an environment with mild smoke, which imposes an emergency situation upon people, but has not been thick enough to physically impede people's movement. Stage 2 represents people's behaviour in an environment with moderate smoke. At this stage, the visual obscuration effect of smoke dominates while people's travel speed decreases almost linearly as the smoke density increases. Stage 3 represents people's behaviour in an environment with extremely dense smoke. The visual obscuration effect becomes so severe that people will find themselves in a nearly darkness situation. At this stage, people rely on perception of touch to make progress or crawling. It should be noted that this curve represents the general occupant behaviour in response to the impact of smoke and the corresponding performance; the real speeds measured in the experiments are expected to distribute around the curve. The probabilities of the typical behaviour observed in these experiments are listed in Table 11.3.

Table 11.3: Typical behaviour observed during experimental trials and the probabilities.

Stage	Identified typical behaviour	Related experiment	Percentage of behaviour observed during experiment	Relative mobility
1	Rushing behaviour	The SHEBA experiment	57.4%	1.10
2	Walking in reduced speed	The SHEBA experiment and the experimental trials conducted by Jin and Wright *et al.*	100%	Linearly decline from 1.10 to 0.37
3	Seeking support e.g. walls and movement by touch or crawling	The experimental trials conducted by Jin and Frantzich & Nilsson	Estimated from Frantzich & Nilsson's data-set	
			80%	0.37

The scheme of the behavioural model for estimating occupant's ability to travel at the desired speed in smoke is shown in Figure 11.8. The occupant's travel speed is dependent on both their initial physiological attributes and their interaction with the environment. The smoke density is divided into three levels. A behavioural factor describing the occupant's response is associated with each level of smoke. The occupant's eventual travel speed is calculated through the mobility associated with each behavioural response.

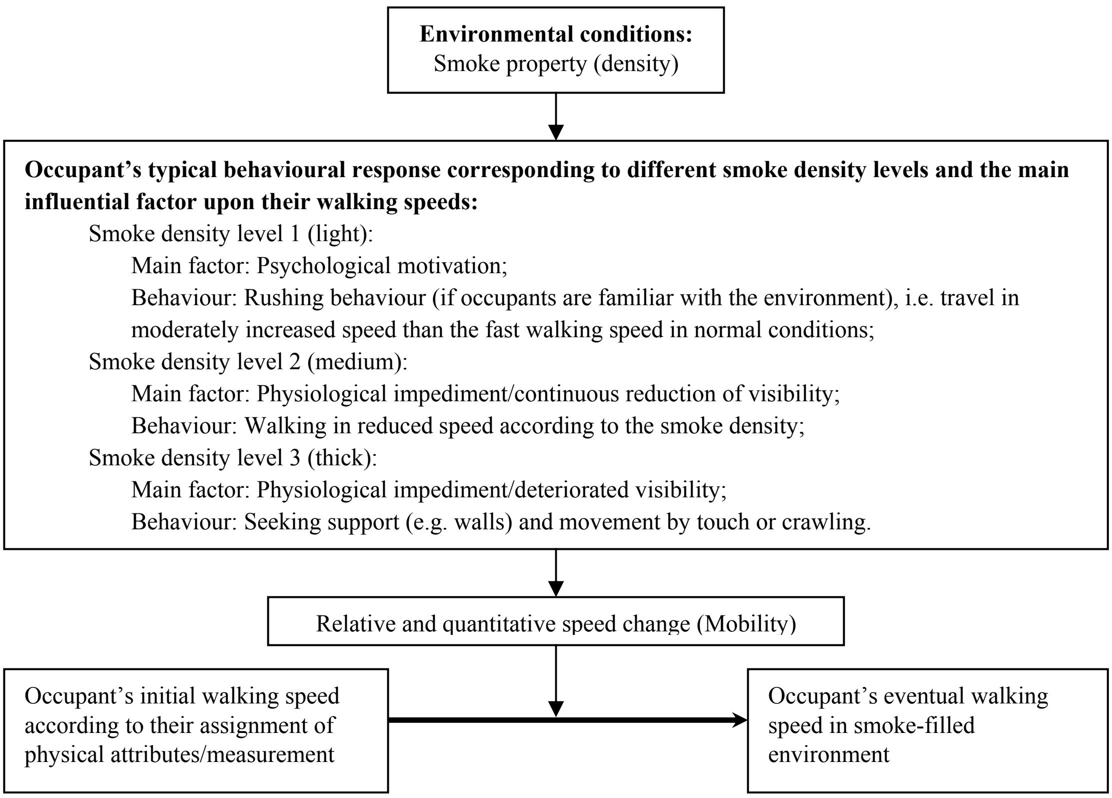


Figure 11.8: The scheme of the behavioural model.

When applied to a specific scenario and population, this model requires the values of four variables: two mobility rates (r_1 and r_2), and two threshold values of smoke density (K_1 and K_2) that segregates the continuous smoke density into the three levels described (see Figure 11.7 and Figure 11.8).

r_1 is the Mobility at the first stage representing occupants' rushing behaviour, which was observed in the SHEBA experiment at a low level of smoke density. r_2 is the Mobility at the third stage representing occupants' behaviour of walking in a 'zigzag' manner or step by step along walls, which were observed in Jin's and Frantzich & Nilsson's experiments at a high level of smoke density. r_2 can also be the rate representing occupants' crawling behaviour at the third stage.

K_1 is the first threshold point which separates stage 1 from stage 2. The influence of psychological motivation as a response to perceive the presence of smoke dominates in stage 1. When the smoke density exceeds K_1, the physiological impediment imposed by the visual obscuration effect of smoke becomes dominant.

K_2 is the second threshold point which separates stage 2 from stage 3. The region between K_1 and K_2 represents the second stage. The mobility within this stage linearly declines from r_1 to r_2, representing a linear relationship between the occupant's travel speed and the smoke density. This linear relationship can be derived from either Jin's non-irritant data-set or the SHEBA data-set at the medium level of smoke density. When the smoke density exceeds K_2, the occupant demonstrates relatively stable performance in terms of travel speed.

This behavioural model is based on the results obtained from the four experiments simulating a smoke-filled environment and using human subjects. The values of the four variables in Table 11.4 derived from these experiments are only given as a recommendation. In reality the transaction from one stage to another stage may not be at a single point, instead it may have a representation of a continuous curve. The model presented here is a simplification of the available data-sets (see also Figure 11.6). It is expected that this model captures the key factors influencing people's egress performance (travel speed), the main behavioural responses of people and their small-scale behaviour in a smoke-filled environment.

Table 11.4: Recommended values of the four variables in the model.

Variable	Recommended value	Value range	Data-set referred
K_1	0.23 (/m)	0.20 ~ 0.25	Jin's Non-irritant data-set, the SHEBA data-set
K_2	2.00 (/m)	1.50 ~ 2.50	Jin's Non-irritant data-set, Frantzich & Nilsson's data-set
R_1	1.142	—	The SHEBA data-set
R_2	0.373	—	Frantzich & Nilsson's data-set

11.4 Summary

This chapter firstly reviewed Jin's study of the influence of smoke upon evacuees in evacuation and the application of Jin's data in an evacuation model to represent the impact of smoke on evacuees' ability to travel at the desired speed. Then the comparable evacuation experimental trials conducted in a smoke-filled built environment by Frantzich *et al*, Wright *et al* and the SHEBA experiment were analysed, including the results produced. The data-sets collected and the small-scale behaviour observed during these experiments provided an opportunity to produce a more comprehensive description of the impact of smoke on evacuees than the original model derived from Jin's work only. Based on the analysis of the additional data collected from these experiments, an improvement on the original model was made through two attempts.

The first attempt focused on the influence of the visual obscuration effect of smoke upon people's ability to travel at their desired speeds and it aims at representing the influence within a wide range of smoke density. A new 'Non-irritant' curve was produced by integrating the data-sets obtained from the experiments conducted by Jin and Frantzich & Nilsson based on the comparable experimental conditions. This new curve is compatible with the Jin 'Non-irritant' curve and it also widely extends the applicable range of smoke density. Analysis of these experiments also highlights the other types of behaviour observed such as travelling at a higher speed than normal fast walking speed and the *wall-following* behaviour. The analysis provided a hint to improve the behavioural response implemented in the original model.

The original modelling approach was based on the performance data measured in specific experimental trials, while the people's behavioural responses are simulated as added features. This approach potentially breaks the natural link between occupant behaviour and performance. To address this issue, the second approach which focussed on people's behavioural responses to exposure to smoke was proposed. This alternative modelling approach links people's behavioural responses (to smoke) with their performance. The behavioural model utilised most of the data available to identify three typical behavioural responses corresponding to three levels of smoke density. The occupant's ability to travel at the desired speed is then linked to the smoke density though their behaviour, i.e. what speed the occupant can achieve is subject to their current behaviour. This approach is compatible with the tendency to focus on representing occupant behaviour in evacuation modelling, and more importantly it relates adaptive occupant behaviour and performance to dynamic environmental conditions.

A similar approach to the behavioural model presented here is reported in a study on pedestrian flow in Russia: Kholshevnikov *et al.* [2008] found that it is not possible to produce a valid general description of the relationship between flow velocity and flow density when they tried to integrate the experimental results from a series of experimental studies on pedestrian flow. To address this issue, Kholshevnikov *et al.* [2008] employed psychophysics and psychophysiology theory to establish a link between pedestrian flow density and emotional state of persons to their travel speeds.

Chapter 12
Conclusions and Future Work

In this chapter, the major outcomes of this research and the applications are initially described. A review is given to summarise how the original research questions posed in Chapter 1 were addressed throughout this dissertation. Finally, the direction of potential development and future work are introduced.

12.1 Conclusions

Signage* is an important component of building wayfinding and safety design (Section 1.1.1, Chapter 1). The importance of signage has been recognized and addressed by relevant safety legislation and building standards, which provide the guidance on the design and use of signage systems within buildings (Section 2.1.1 and Section 2.2, Chapter 2). In principle [BS 5499-4:2000; ISO 16069:2004], signs should be positioned at places where direct sight of an exit is not available and where its location may be in doubt. The information conveyed by the signs should clearly identify the direction and location of the means of escape from any place in the building to a place of safety or a final exit. Whereas the guidance [BS 5499-4:2000; ISO 16069:2004] reflects good practice (i.e. ensuring signs are provided where necessary and can be seen), it does not address how occupants perceive and utilise signage in an emergency (Section 2.2.3.2, Chapter 2). The effectiveness of signage systems is often left to performance-based analysis to evaluate the impact of signage as part of wayfinding and safety design of the buildings. However, assumptions and simplifications prevail in the modelling and engineering approaches employed. Most importantly, it is often assumed that if the signage system is compliant, it will be effective in conveying the specified information to the occupants and that this will be correctly interpreted and utilised by them (Section 1.1.2, Chapter 1).

In reality, the interaction between occupants and signage in an emergency evacuation is a complex process influenced by a number of physical, cognitive and psychological factors

* Safe condition signs [BS5499-1:2002], including escape route signs, exit signs and fire exit signs with directional designation, are the only type of signs that are addressed in this dissertation, unless otherwise stated.

(Section 2.1, Chapter 2). The situation could be more complex if there is fire and/or smoke present (Section 2.3, Chapter 2). The presumed effectiveness of signage systems in assisting people's wayfinding during an evacuation may be overly optimistic. The under utilisation of emergency signage has been demonstrated both in previous disasters and in experimental studies (Section 2.1.2, Chapter 2). The potential benefits of signage to evacuees may be less than expected.

Despite the importance of signage and the need to address the effectiveness of signage in performance-based analysis, only a few evacuation models include a representation of signage systems (Section 2.4, Chapter 2). These models can simulate the influence of signage on the occupant's exit route and/or exit selection, but simple approaches are employed due to a lack of relevant data: either the models let the user assign the efficacy of the signage system, or employ arbitrary 100% detection and compliance rates in representing the interaction with signage. In general, there is a severe lack of consideration of the potential factors involved in the interaction with signage amongst these model representations (Section 2.4.2.2, Chapter 2).

The concerns about the effectiveness of signage systems in practice and the limitations of the existing model representations of the interaction between occupants and signage provided the direction for the research in this dissertation.

In the following sections, the major outcomes of the research along with the potential applications are introduced, followed by a summary of this research addressing the original research questions, as set out in Chapter 1.

12.1.1 Major Outcomes and Applications

This dissertation presents an improved understanding of occupant interactions with signage systems and smoke during an evacuation through four pieces of work.

Firstly, an extensive literature review was conducted (Chapter 2), which addressed the current understanding of the interaction with signage, the guidance on design and use of signage systems, studies on the impact of smoke and the current approaches to represent the interactions with signage and smoke in existing models. This review provided the basis of the research presented in this dissertation - informing the factors addressed and the manner in which they were addressed.

Secondly, the dissertation described the design and performance of a series of experimental trials that collected the data on the visibility limits of signage (Chapter 4) and the interaction with signage (Chapter 6). The data collected is crucial for establishing a realistic estimate of the signage visual catchment area (Chapter 5) and a better understanding of the interaction with signage (Chapter 7). This data was previously lacking in the research of behavioural performance of evacuees as well as relevant safety legislation and standards, since no one else has published data like this.

Thirdly, the dissertation analysed the existing published experimental data on impact of smoke on signage visibility, occupant egress performance and behaviour [Jin 1978, 1997, 2008; Jin & Yamada, 1985, 1989; Frantzich & Nilsson, 2004; Wright *et al.*, 2001b; Galea *et al*. 2001]. Based on the analysis of the data and experimental conditions, the impact of smoke on signage visibility was introduced in the calculation of the signage visual catchment area (Chapter 10), and a comprehensive representation of the impact of smoke on occupant evacuation behaviour was provided to improve the previous representation (Chapter 11).

Finally, the dissertation described the implementation and demonstration of a novel signage model (Chapter 8) for evacuation modelling. This new signage model is partly based on the previous research carried out by Filippidis *et al.* [2001, 2003, 2006], and mostly utilises the results from analysing the data collected from the experimental studies performed (chapters 4, 5, 6, and 7). The work presented in this dissertation represents the first time that signage systems and occupant interaction with signage have been modelled to this degree of sophistication.

When assessing the evacuation capability of a building using computer simulation, it is common practice for engineers to explore two base scenarios, which provide an upper and lower limit to a likely evacuation performance. The scenario for the upper limit typically involves all the agents utilising the main exits only and ignoring emergency exits (hence the signs indicating emergency exits). In contrast, the scenario for the lower limit typically involves all the agents utilising all available exits and assuming either a good understanding of the structure among the agents or an optimal use of wayfinding information by the agents. These two scenarios typically provide a wide and, in many cases, unrealistic range of egress times. In a real emergency situation, at least some occupants, especially those who are unfamiliar with the structure, may be expected to utilise the signage system to assist in wayfinding (which is the purpose of providing signage in buildings), especially in situations where staff are not available to guide occupants to the emergency exits (i.e. having to rely more on the signage available), or where evacuees are specifically reminded to use the signage as part of the procedural response (e.g. an announcement over the voice alarm). Therefore, it is essential to appropriately represent occupants' exit knowledge and adaptive decision-making processes concerning the selection of the most viable available exit according to wayfinding information. In situations in which unfamiliar occupants rely on the signage system to access the emergency exits (or exits that were previously unfamiliar to them), a more realistic estimate of the lower limit of expected egress times can be obtained using the signage detection and compliance data presented in this dissertation along with the new signage model.

The newly developed model, presented here, should allow engineers to test the effectiveness and impact of signage systems upon emergency movement and potentially, non-emergency movement. It should also allow them to establish the relative impact of including more signs, improving training (e.g. encouraging people to be more attentive to signage), the exact positioning of signs and the type of design used. In effect, this dissertation has improved the evacuation model developed as a design tool.

12.1.2 Addressing the Original Research Questions

The following sections describe how the objectives of the original research questions posed in Chapter 1 have been met in the work presented.

Question 1: How do people interact with signage in buildings?

The interaction between occupants and signage has three aspects to be addressed: (1) the visibility of sign, (2) the perception of sign and (3) the interpretation and compliance of signage information.

(Q1.1) *Visibility of sign*: What is the definition of signage visibility? What are the corresponding requirements to achieve the visibility in current legislation and standards? What is the physical extent within which people can reliably resolve the sign? What are the conditions for reliably resolve the sign?

In current legislation and standards [BS5499-1:2002; BS5499-4:2000; ISO 3864-1:2002], the visibility of sign is prescribed through the maximum viewing distance, which is calculated as the product of the size of the detail (to be resolved by occupants) on the sign and a distance factor. The selection of the detail varies in the regulations and that it can be either text height, graphics symbol height or sign height. The distance factor varies with the type of sign and the lighting conditions. The calculation of the maximum viewing distance provides a practical means for assessing the visual catchment area (VCA) of a sign within which people can receive information from the sign. The VCA estimated by this method has a semi-circular representation centred on the sign, with its radius given by the maximum viewing distance. However, this method ignores the impact of the angular distortion on people reading the sign at a non-perpendicular angle (Section 2.2.3.1, Chapter 2).

In order to examine the influence of the angular distortion on the visibility of signage, a series of experimental trials, described in Chapter 4, were designed and conducted. In these trials three standard exit signs including text of different heights were successively placed on a white board positioned at one end of a well-lit corridor. Participants were instructed to approach the sign slowly from the other end of the corridor until at least half of the text was legible. The distance was measured as a conservative estimation of the maximum viewing distance of the sign at the corresponding viewing angle. This process was repeated while the sign was set to a series of pre-defined angles in relation to the participant's approach to the sign.

It was found for all three signs that the maximum viewing distance is not only dependent on the height of text, but also the viewing angle (Chapter 5). As the viewing angle increases, the maximum viewing distance decreases in a non-linear manner. This is the result of the angular separation of the lettering on the sign decreasing as the angle of observation increases, while the human eye has a minimum angular resolution. In addition, the empirical VCA of the sign tested was estimated by connecting the average maximum viewing distance measured at different viewing angles. The VCA determined in this way is a slightly flattened circle that is tangent to the surface of the sign, with its minor radius equal to the previously defined semi-circle or half of that if the safety factor is considered. These results are valuable in their own right as they more accurately define the visibility limits of signs than what have been defined by the current regulations for designing signage systems. The new and more realistic representation of the signage catchment area corrects the overly optimistic regulatory assumptions.

(Q1.2) *Perception*: What is the current understanding on how people interact with signage? Given that the sign is visible, are people always able to perceive the sign? If not, how likely do people perceive or register seeing the sign? What are the factors that may influence the perception of the sign?

(Q1.3) *Interpretation and compliance*: Given that people already perceive and read the sign, what is the likelihood of people correctly interpreting and complying with the information conveyed by the sign?

Question Q1.2 and Q1.3 are addressed together. Research on people's wayfinding behaviour within the built environment has identified signage as an important form of environmental information that influences people's wayfinding performance [Weisman, 1981, 1985]. Two aspects of the influence were demonstrated in experimental studies collected in the process of this research (Section 2.1.2.2, Chapter 2). Firstly, a positive relationship between a signage system and wayfinding performance was observed [Carpman *et al*., 1984; Corlett *et al*., 1972; O'Neill, 1991]. Secondly, the efficacy of signage could be limited: not only because signage could not compensate for the complex of building layout [O'Neill, 1991] and architectural failures [Arthur & Passini, 1992], but also because occupants did not always utilise or remember seeing the signs available to them [Weisman, 1985; McClintock *et al.* 2001]. The above results are useful in understanding the effectiveness of signage systems. However, these results concerning the interaction between occupants and signage were obtained under normal, everyday conditions; in addition, the researchers focused on the effectiveness of the specific signage systems within the test systems examined, but not the relationship with the environment where the signs were positioned, nor the process in which occupants interact with an individual sign and the factors that may influence the likelihood of occupants perceiving and utilising the sign. There was a lack of relevant published data concerning how occupants perceive, interpret and use the information conveyed by emergency signage from the current understanding of the interaction with signage (Section 2.1.2.2 and Section 2.1.2.3, Chapter 2).

To address the lack of data on occupant interaction with signage, additional experimental data was collected and is described in Chapter 6 and Chapter 7. The experiment involved measuring the impact of a standard signage system on a population of 68 test subjects who were instructed to individually vacate a building as quickly as possible via any means they thought appropriate. The evacuation path included a number of decision points at which emergency signage was available to indicate the appropriate escape path/exit door. The purpose of this experiment was to determine the likelihood that evacuees faced with a route decision point, who are located within the VCA of an emergency sign, will (a) perceive the sign, (b) correctly interpret its information and (c) correctly act upon the information. The experimental method examined an individual's interaction with signage in controlled experimental conditions: it did not take account of other possible influencing factors such as the presence of fire effluent and the interaction with other occupants.

Through analysis of data derived from questionnaires and video footage, the number of participants who perceived and utilised the signage information to assist their egress in the experiment was determined (Chapter 7). The experimental findings suggest that for standard reflective escape route signs measuring 0.1×0.3 m when observed under well-lit lighting conditions *in relatively open circulation spaces* that

- 38% of participants who are unfamiliar with the building layout and who are within the VCA of a sign will actually perceive the sign. Of those who perceive the sign, some 97% will use the information to assist them in wayfinding.
- For those participants who are familiar or partially familiar with the building layout both probabilities are slightly reduced (30% and 94%).
- The differences in both perception and acceptance probabilities between unfamiliar and familiar participants are statistically insignificant.

The experimental findings also suggest that for the same type of signs when observed under well-lit lighting conditions *in relatively confined circulation spaces* that

- 75% of participants who are unfamiliar with the building layout and who are within the VCA of a sign will actually perceive the sign (For participants who are familiar or partly familiar with the building layout there was insufficient data collected to draw a conclusion).
- Of those who perceive the sign, some 94% will use the information to assist them in wayfinding.

The difference in perception probabilities between unfamiliar participants in open circulation spaces and unfamiliar participants in confined circulation spaces is statistically significant; however, the difference in acceptance probabilities is not statistically significant (Section 7.2.4, Chapter 7). These results suggest that it is less likely for occupants to perceive signs positioned in relatively open spaces than signs of the same size and type positioned in confined spaces; once occupants perceive the signs, regardless of the nature of the space, the majority of them will correctly interpret and use the information to assist them in wayfinding. The nature of the space where the sign is positioned influences an occupant's perception of the signs; however, it does not influence the manner in which occupants interpret and utilise the information conveyed by the signs if they successfully perceive the signs.

The experimental findings also suggest that those participants who detect a sign are more likely to perceive and use the direct successor of the sign than those who did not; while detecting a sign has no significant impact on the participant detecting the indirect successor of the sign (Section 7.2.5, Chapter 7). In situations where the participant approaches the sign so that they are directly facing the sign, on average those participants who detected the sign take less than half as long to make a route decision as those participants who failed to detect the sign (Section 7.2.6, Chapter 7). The differences in detection times are statistically significant, irrespective of whether the participants are familiar with the building layout or not. This demonstrates that the exit sign, if detected, effectively facilitates the occupant's decision making process.

Given that smoke may be present during an evacuation, it is important to take the impact of smoke upon signage visibility into account when representing the interaction between occupants and signs, and their consequent behavioural response to smoke (Section 2.3, Chapter 2).

Question 2: How does the presence of smoke influence people's interaction with signage and their evacuation behaviour?

(Q2.1) How does smoke influence the visibility of signs?

The presence of smoke can reduce the visibility of signs by obscuration effect and irritant effect [Jin 1978, 1997, 2008; Jin & Yamada, 1985]. The direct luminous fluxes from the signs can be scattered and absorbed by smoke particles, effectively reducing the intensity; and the ambient luminous fluxes that are also scattered by smoke particles can be superimposed on the fluxes from the signs, effectively reducing the contrast between the signs and the background. In addition, occupants may not keep their eyes open in highly irritant smoke, effectively requiring a larger contrast value than in non-irritant smoke to read the sign. Signage visibility in smoke is often defined through the contrast threshold [Jin, 1978, 2008;

Sychta, 1997; Zhang & Rubini; 2009]. A frequently used definition of the visibility of sign is the distance by which the contrast between the brightness of the sign and that of the background is reduced to a threshold value (Section 2.3.1, Chapter 2).

(Q2.2) How does smoke influence people's travel speed and evacuation behaviour?

Smoke also affects the visibility of other objects such as walls and floors in buildings. The reduced visibility makes it difficult for occupants engulfed in dense non-irritant smoke (or irritant smoke) to discern the environment and consequently, they are unable to travel at desired speed and move accurately towards the desired target [Jin 1978, 1997, 2008; Jin & Yamada, 1985; Frantzich & Nilsson, 2004] (Section 2.3.2, Chapter 2).

(Q2.3) What are the results and findings from relevant studies?

It was found through experimentation [Jin 1978, 1997, 2008; Jin & Yamada, 1989] (Section 2.3.1, Chapter 2) that human visibility levels at both the obscuration threshold of an exit sign and the legible threshold of text on the signs are impaired as the smoke density increases. The impact of smoke on signage visibility can be expressed as a constant product of the visibility distance and the smoke density. The constant varies with the properties of the signs (e.g. light-emitting, reflecting).

Human egress performance and behaviour in smoke were also studied through experimentation [Jin, 1978, 1997, 2008; Wright *et al.*, 2001b; Galea *et al.*, 2001; Frantzich & Nilsson, 2004]. One commonly observed pattern of behaviour in the experiments is that participants tend to slow down as the smoke density increases. When the smoke density further increases to a certain level (as if in darkness), they are unable able to walk straight or make unaided progress [Jin, 1978, 1997; Frantzich & Nilsson, 2004] (Section 2.3.2, Chapter 2).

Finally, questions regarding the representation of the interaction with signage and the influence of smoke in computer models are now addressed.

Question 3: How are evacuation models influenced by the understanding of the interaction with signage and the impact of smoke?

(Q3.1) How are signage systems currently modelled in existing models?

Most pedestrian (including evacuation and circulation) computer models conduct route calculations by following an "optimistic" assumption regarding wayfinding; i.e. agents 'know' the appropriate exit route. The occupant choice of escape route/exit is therefore independent of wayfinding information in the environment. This approach excludes signage as a key factor in route selection and prevents the models from examining the impact of the design of different signage systems.

A few models such as PEDROUTE, buildingEXODUS and MASSEgress etc attempt to incorporate a representation of the signage system and simulate the influence of signage on an occupant's exit route and exit choice. However, due to a lack of relevant and sufficiently detailed data, the key aspects of the interaction, i.e. the visibility, perception and interpretation of signage, are either implicitly represented or ignored (Section 2.4.2.2, Chapter 2).

(Q3.2) How is the impact of smoke upon the interaction with signage modelled in existing models? How is the impact of smoke upon people's travel speed and evacuation behaviour modelled in existing models?

Prior to this research, no known model takes account of the impact of smoke upon the interaction with signage in evacuation simulation. The common forms of the influence of smoke modelled are the impact upon occupant's exit selection and travel speeds (Section 2.3.2, Chapter 2). buildingEXODUS, for instance, simulates occupant's adaptive exit selection based on the behavioural data collected from real fire incidents. The model also represents the impact of smoke on occupant travel speed and local behaviour based on experimental findings (Section 3.3.2.3, Chapter 3).

(Q3.3) What are the limitations of the current representation of the interaction between occupants and signs? What are the limitations of the current representation of the influence of smoke? How can the models be improved?

The buildingEXODUS evacuation model is one of a few models that includes a representation of the interaction with signage as part of the agent wayfinding process (Section 3.3.2.1 and Section 3.3.2.2, Chapter 3). It also takes account of the influence of smoke upon agent evacuation behaviour (Section 3.3.2.3, Chapter 3). Compared with the other models (Section 2.4.2.2, Chapter 2), buildingEXODUS has a more explicit modelling framework to represent the process of interaction with signage. This framework takes account of the physical visibility of signage as well as the process of occupants perceiving a sign and acting on the information perceived. However, it has several limitations. First, the visibility of signage is calculated based on the maximum viewing distance defined in relevant regulations. This method has been demonstrated to be inadequate because it lacks consideration of the situation where an occupant may be approaching the sign at a non-perpendicular angle (Section 2.2.3.1, Chapter 2). In addition, it does not take account of the influence of smoke upon signage visibility. Second, the model imposes arbitrary (mostly ideal) detection and compliance probabilities on agents. These probabilities are postulated, and are not based on experimental data, nor are they consistent with the existing understanding on how people may use signage (Section 2.1.2.2 and Section 2.1.2.3, Chapter 2). Similar limitations also exist within the other models which attempt to simulate the interaction between occupants and signs (Section 2.4.2.2, Chapter 2).

Given the importance of signage in assisting building occupants in an evacuation, and the need to correctly represent the impact of signage on occupant evacuation behaviour (Section 1.1, Chapter 1), an attempt has been made to improve the current representation of the interaction between occupants and signs within buildingEXODUS (Chapter 8). The improvement addresses the limitations of both the current understanding of how people interact with signage and the existing representation in the model. This is achieved based on the findings gathered through the experimental studies on signage visibility (Chapter 4, Chapter 5) and occupant interaction with signage (Chapter 6, Chapter 7).

The research presented in this dissertation has improved the method of calculating the physical visibility of signage, as used by buildingEXODUS, by taking account of the influence of both the angular distortion and smoke. Firstly, the new method (Section 8.2.1, Chapter 8) produces a circular representation of the visual catchment area (VCA) of the sign to replace the previously defined semi-circular representation (Section 8.1.1, Chapter 8). This new representation reflects the experimental findings that the maximum viewing distance of the sign is dependent on the viewing angle (Chapter 5). Secondly, the influence of smoke upon the signage visibility has been incorporated into the calculation of the VCA through two methods (Chapter 10). The first method integrates the product of local extinction coefficient and the segment length along the line of sight from the sign, and then compares the result with

Jin's constant [Jin 1978, 1997, 2008] to determine the termination distance of the sign in smoke. The second faster, but less accurate method uses the average smoke density within the VCA of the sign to calculate the termination distance in all directions. The new VCA model, presented in Chapter 8 and Chapter 10, more accurately defines the visibility limits of signage both in a clear environment and in smoke than the previous method.

In addition to the impact of smoke on signage visibility, a comprehensive representation of the impact of smoke upon occupant travel speed and behaviour is produced by combining the available experimental results through an analysis of the experimental conditions and configurations (Chapter 11). In particular, a novel approach is presented (Section 11.3.4, Chapter 11), for the first time, to try to integrate the experimental results based on occupant behavioural responses to changing conditions. This work improves the original representation, utilised by buildingEXODUS V4.0, based on Jin's data [Jin 1978, 1997].

Finally, the signage interaction data (Chapter 7) collected through experimentation (Chapter 6) has been implemented within the buildingEXODUS evacuation software (Section 8.2.2, Chapter 8). Effectively the experimental data replaced the idealised 100% probabilities of perception and compliance when occupants are within the VCA of a sign and are travelling in a direction which allows the sign to be seen. The interaction process involves an occupant perceiving the sign and utilising the information to assist their exit selection. The process begins when an occupant enters the VCA of a sign. The new signage model assigns the probability of the occupant perceiving the sign according to (a) the relative orientation between the occupant and the sign and (b) the nature of the space where the sign is positioned. Since the influence of the relative orientation had on the likelihood of an occupant detecting a sign was not addressed in this experimental study, it is represented using the original sigmoid curve from the previous signage model, as utilised in buildingEXODUS V4.0 (Section 8.1.2, Chapter 8). The influence of the other factors involved in the interaction is represented using the detection rate obtained in the experiment. If the occupant detects the sign, whether the occupant acts on the signage information perceived is represented through the compliance rate obtained in the experiment. If the occupant accepts the information conveyed by the sign, the corresponding exit knowledge associated with the sign will be added to the occupant's Occupant Exit Knowledge. It is then assumed that the occupant will compare this new knowledge with existing exit knowledge to find an optimal egress route leading to the exterior of the building or a place of safety.

The application of the new signage model in evacuation simulation has been demonstrated through two simulation cases (Chapter 9). The results from the simulations indicate that signs can be useful in directing people to emergency exits and hence reducing egress times for both large and complex structures. In the ideal situation simulated by the previous signage model, as utilised in buildingEXODUS V4.0, where signs had 100% detection, interpretation and compliance rates (assumed by the previous signage model), evacuation times could be reduced to a level comparable to the situation in which all the occupants had perfect knowledge of the exit positions. However, in the more realistic and representative situation using the experimental data by the new signage model, the low detection rate associated with signs greatly constrains the possible improvement in egress times that may be achieved. The results also show the influence of different designs of signage system (VCA coverage and position of signs) may have on the evacuation performance.

12.2 Future Work

The work summarised in Section 12.1 describes an attempt to study the behavioural performance of occupants during an evacuation through an experimental approach. It mainly addresses the influence of exit signs upon evacuating occupants. Based on the experimental results obtained, an advanced signage model has been developed to improve the representation of the interaction between occupants and signage in evacuation modelling. The experimental research conducted together with the signage model developed does not address all aspects of the interaction with signage; besides, the results obtained raise new concerns to the current design of emergency signage. Potential improvement and fields of interest are now suggested for future work.

12.2.1 Improve the Signage Model

The new signage model utilised part of the experimental findings obtained from the trials, i.e. the perception and compliance probabilities. The other findings, such as the impact of signage on an occupant’s decision time and the tendency of an occupant continuously making use of the other signs along the egress route (Section 7.2.5 and Section 7.2.6, Chapter 7), are currently not included. These findings could be implemented in a future development of the model to more accurately represent occupant interaction with signage.

The new signage model calculates the probability of an agent detecting a sign according to the expected number of steps an agent is going to travel across the VCA of the sign. A simplification in the implementation of the model assumes that the agent will travel across the VCA along a fixed direction of travel in which they enter the VCA (Section 8.2.2.4, Chapter 8). If the agent changes the direction of travel during progress within the VCA (e.g. due to the presence of obstacles and other agents), it will influence the estimate of the total number of steps and hence the accuracy of the detection probability assigned to them at each step. Therefore, it is necessary to improve the prediction of the agent's direction of travel within the VCA to enhance the model. This can potentially be achieved by examining the agent's immediate goal of travel on the other side of the VCA before they travel across the VCA.

12.2.2 Improve the Design of Emergency Signage

The experimental results (Chapter 7) together with the simulation results (Chapter 9) suggest that current emergency guidance signs are less effective as an aid to wayfinding than they potentially could be. However, given the correct comprehension and high rate of compliance of signage information found in the experimental studies presented in this dissertation, signs are likely to be more effective if they can be made more attractive. This can be done in a number of ways such as increasing the size of the sign, making the sign standout more from the background, or introducing additional sensory stimuli such as flashing lights and auditory signals. However, it is essential that any changes made to the design of the emergency sign do not inadvertently decrease the simplicity and clarity of the information conveyed by the sign. The potential improvement of any changes made to the design can be tested by following the same procedure presented in this dissertation (Chapter 6), and compared against the results obtained through the examination of the current design of emergency signs (Chapter 7).

12.2.3 Extend the Representation of Signage Visibility

This experimental study of signage visibility addressed the visibility of the text component on reflective signs under normal lighting conditions. Currently the signage model utilises the height of text on the sign to assess the VCA of the sign. With increasing emphasis on the inclusion of graphical symbol in signage design by legislation and standards [the Health and Safety (Safety Signs and Signals) Regulations 1996; BS5499-4:2000; ISO 3864-1:2002] the effect of this will need to be taken into account in the model when performing the VCA calculation. In addition, other influencing factors, such as lighting conditions and the type of signs upon signage visibility, should also be included so that the visibility of signs in a variety of situations can be correctly represented in the model.

12.2.4 Further Testing and Validation

Since this is the first attempt to collect data regarding how occupants perceive, interpret and use the information conveyed by emergency signage under egress situations involving complex building structures, there is no other similar published data to compare with. It was felt that more data from comparable experimental work and evacuation are required in order to strengthen the credibility of the results produced and to validate the new signage model.

12.2.5 Other Influencing Factors and Experimental Method

The interaction between occupants and signs is influenced by a variety of factors. As the first attempt to study the interaction, the design of the experiment focused on a few key factors and examined an individual's interaction with signage in ideal conditions. The experimental results were not fully understood. For instance, the other potential factors such as personal characteristics (age, gender, identity and experiences) and participants' consideration during the wayfinding task were not addressed. In addition, compared with a more general evacuation situation in a built environment, the interaction with signs is likely to be influenced by the interaction with other occupants, group interaction and the presence of visual clutter and fire effluent within the environment. The influence of these factors is left for further data analysis and experimental study in the future.

The design and conduction of the signage experimental trials include a substantial amount of effort and besides, the trials are often restricted by the layout, availability of the buildings used and staffing costs etc. The experiment can potentially be simplified by utilising techniques such as virtual reality [Shil *et al.*, 2000] and 3D image projection [Akizuki *et al.*, 2009, 2010] to create a virtual environment in which participants can navigate and browse. New experimental methods and the validity of using these techniques in the research should be explored to facilitate future experimental studies.

The work presented in this dissertation has provided a novel and important contribution to the field – improving our understanding of key procedural and behavioural phenomena, developing models to represent these phenomena and then implementing these models within a state-of-the-art tool. This should allow engineers and researchers to more effectively and reliably examine the impact of signage systems upon pedestrian and evacuee movement, improving both procedural and spatial design in both emergency and non-emergency scenarios.

REFERENCES

Akizuki, Y., Iwata, M., Okuda, S., Tanaka, T., 2009. Setting conditions of signs in escape routes by configuration factor. *Journal of Environmental Engineering (Translations of AIJ)*, 74(641), pp.767-773.

Akizuki, Y., Okuda, S., Iwata, M., Tanaka, T., 2010. Study on the visual environment designs for effective evacuation guidance - Measurement and evaluation of sign installation in escape routes. *Proceedings of the 12th International Fire Science & Engineering Conference, Interflam 2010*, University of Nottingham, UK, Interscience Communications Ltd: London, Vol. 2, pp.1479-1485, ISBN 978-0-9541216-6-2 (Vol.2).

Arthur, P., Passini, R., 1992. *Wayfinding: People, Signs and Architecture*, McGraw-Hill Ryerson Ltd.: Whitby, Ontario, ISBN 0-07-551016-2.

Barton, J., Leather, J., 1995. Paxport - Passenger and Crowd Simulation. *Passenger Terminal'95*, pp.71-77.

Beaumont, P., Gray, J., Moore, G., Robinson, B., 1984. Orientation and way-finding in the Tauranga Department Building: A focused post-occupancy evacuation. *Proceedings of the 15th Annual Conference of the Environmental Design Research Association*, D. Duerk & D, Campbell (Eds.).

Bensilum, M. & Purser, D. A., 2003. Grid Flow: an object-oriented building evacuation model combining pre-movement and movement behaviours for performance-based design. *Fire Safety Science – Proceedings of the Seventh International Symposium*, Worcester, Massachusetts, USA, pp.941-952, ISBN 0-9545348-0-8.

Benthorn, L., Frantzich, H., 1999. Fire alarm in a public building: how do people evaluate information and choose evacuation exit? *Fire and Materials*, Special Issue: Human Behaviour in Fire, 23(6), pp.311-315, doi:10.1002/(SICI)1099-1018(199911/12).

Best, R.L., 1977. *Reconstruction Of A Tragedy: The Beverly Hills Supper Club Fire*. Southgate, Kentucky, May 28, 1977, NFPA, ISBN 0-87765-113-2.

Bryan, J.L., 1977. Smoke as a Determinant of Human Behavior in Fire Situations (Project People). National Bureau of Standards, Center for Fire Research, NBS-GCR-77-94: Gaithersburg.

Bryan, J.L., 2002. A selected historical review of human behavior in fire. *Fire Protection Engineering*, Issue 16, pp.4-10.

British Standards Institution, 1990. *BS 5499-1:1990 Fire safety signs, notices and graphic symbols. Specification for fire safety signs*, BSI: London, ISBN 0-580-18830-2.

British Standards Institution, 1999. *BS 5266-1:1999 Emergency lighting. Code of practice for the emergency lighting of premises other than cinemas and certain other specified premises used for entertainment*, BSI: London, ISBN 0-580-33044-3.

British Standards Institution, 1999. *BS 5266-7:1999 Lighting applications - Emergency lighting*, BSI: London, ISBN 0-580-32992-5.

British Standards Institution, 2000. *BS 5499-4:2000 Safety signs, including fire safety signs - Part4: Code of practice for escape route signing*, BSI: London, ISBN 0-580-33205-5.

British Standards Institution, 2002. *BS 5499-1:2002 Graphical symbols and signs - Safety signs, including fire safety signs - Part 1: Specification for geometric shapes, colours and layout*, BSI: London, ISBN 0-580-38258-3.

British Standards Institution, 2005. *BS 5266-1:2005 Emergency lighting. Code of practice for the emergency lighting of premises*, BSI: London, ISBN-0-580-46820-8.

Buckmann, L.T., Leather, J.A., 1994. Modelling Station Congestion The Pedroute Way. *Traffic Engineering And Control*, 35(6), pp.373-377.

Bukowski, R.W., Tanaka, T., 1991. Towards the Goal of a Performance Fire Code. *Fire and Materials*, 15(4), pp.175-180.

Bukowski, R.W., 1996. Setting Performance Code Objectives - How Do We Decide What Performance The Codes Intend? *Proceedings of the 7th International Fire Science and Engineering Conference, Interflam 1996*, Cambridge, England, Interscience Communications: London, pp.555-561.

Bulman, E., Clifford, P., 1995. Customer Service. Interchangeable? *Passenger Terminal World*, pp.18-23.

Canter, D., Matthews, R., 1976. The Behaviour of People in Fire Situations: Possibilities for Fire research. Borehamwood: Fire Research Station.

Canter, D. (Ed.), 1980. Fires and Human Behavior. John Wiley & sons: New York.

Carpman, J. R., Grant, M., Simmons, D. A., 1984. No more mazes: Research about design for wayfinding in hospitals. Ann Arbor, MI: Patient and Visitor Participation Project, University of Michigan Hospitals.

Chooramun, N., Lawrence, P.J., Galea, E.R., 2010. Implementing a Hybrid Space Discretisation Within An Agent Based Evacuation Model. *Proceedings of the 5th International Conference on Pedestrian and Evacuation Dynamics*, NIST, Maryland, USA, pp.449-458.

Collins, B.L., Dahir, M.S., Madrzykowski, D., 1992. Visibility of Exit Signs in Clear and Smoky Conditions. *Journal of the Illuminating Engineering Society*, 21(1), pp.69-84.

Comeau, E., Duval, R.F., 2000. Dance Hall Fire Gothenburg, Sweden, October 28, 1998. Fire Investigations, NFPA: Quincy, MA 02269 USA.

Corlett, E.N, Manenica, I., Bishop, R.P., 1972. The design of direction finding systems in buildings. *Applied Ergonomics*, 3(2), pp.66-69.

Council Directive 92/58/EEC of 24 June 1992 on the minimum requirements for the provision of safety and/or health signs at work.

Creak, J., 1997. Viewing Distances. *Means of Escape*, Liza Murley (ed.), Means of Escape: Essex, UK, issue 1, pp. 18-22.

Daamen, W., Hoogendoorn, S.P., 2003. Qualitative Results from Pedestrian Laboratory Experiments. *Proceedings of the 2nd International Conference on Pedestrian and Evacuation Dynamics*, Galea ER (ed.), CMS Press: Greenwich, UK, pp.121-132, ISBN 1-904521-08-8.

Daamen, W., 2004. *Modelling Passenger Flows in Public Transport Facilities*. PhD Thesis, Delft University of Technology.

Doheny, J., Fraser, J., 1996. MOBEDIC - A Decision Modelling Tool For Emergency Situations. *Expert Systems With Applications*. 10(1), pp.17-27.

Ewer, J., Grandison, A., Jia, F, Galea, E., Knight, B., Patel, M., 2007. *User Guide and Technical Manual, SMARTFIRE V4.1*. Fire Safety Engineering Group, the University of Greenwich.

Fennell, D., 1998. *Investigation into the King's Cross Underground Fire*. HMSO: London, ISBN 0-10-104992-7.

Filippidis, L., Galea, E.R., Lawrence, P.J., Gwynne, S., 2001. Visibility catchment area of exits and signs. *Proceedings of the 9th International Fire Science and Engineering Conference: Interflam 2001*, Edinburgh, Scotland, Interscience Communications Ltd: London, Vol 2, pp.1529–1534, ISBN 0 9532312 9 1 (Vol. 2).

Filippidis, L., Gwynne, S., Galea, E.R., Lawrence, P.J., 2003. Simulating the Interaction of Pedestrians with Wayfinding Systems. *Proceedings of the 2nd International Conference on Pedestrian and Evacuation Dynamics*, Galea ER (ed.), CMS Press: Greenwich, UK, pp.39-50, ISBN 1-904521-08-8.

Filippidis, L., Galea, E.R., Gwynne, S., Lawrence, P.J., 2006. Representing the Influence of Signage on Evacuation Behaviour within an Evacuation Model. *Journal of Fire Protection Engineering*, 16(1), pp.37-73, doi:10.1177/1042391506054298.

Filippidis, L., Lawrence, P.J., Galea, E.R., Blackshields, D, 2008. Simulating the Interaction of Occupants with Signage Systems. *Proceedings of 9th IAFSS Symposium*, Karlsruhe, Germany, pp.389-400, doi:10.3801/IAFSS.FSS.9-389.

Fire Precautions (Workplace) Regulations 1997 (SI No. 1997/1840), The Stationery Office: London, ISBN 0-11-064738-6.

Fire Precautions Act 1971: Guide to Fire Precautions in Existing Places of Work That Require a Fire Certificate, HMSO: London, ISBN 0-11-341079-4.

Francis, R.L., Saunders, P.B., 1979. EVACNET: Prototype Network Optimization Models for Building Evacuation. National Bureau of Standards, NBSIR 79-1593.

Frantzich, H. and Nilsson, D., 2004. Evacuation experiments in a smoke filled tunnel. *Proceedings of the 3rd International Symposium on Human Behaviour in Fire*, Belfast, UK, Interscience Communications Ltd: London, pp.229-238, ISBN 0-9541216-6-X.

Fraser-Mitchell, J.N., 1999. Modelling human behaviour within the fire risk assessment tool CRISP. *Fire and Materials*, 23(6), pp.349-335.

Fruin, J.J., 1971. Pedestrian planning and design (Revised Edition, 1987). ELEVATOR WORLD, INC, USA.

Galea, E.R., Owen, M., Lawrence, P.J., 1996a. Computer modelling of human behaviour in aircraft fire accidents. *Toxicology*, 115(1-3), pp.63-78.

Galea, E.R., Owen, M., Lawrence, P.J., 1996b. Emergency Egress from Large Building Under Fire Conditions Simulated Using the EXODUS Evacuation Model. *Proceedings of the 7th International Fire Science and Engineering Conference: Interflam'96*, St John's College, Cambridge, England, pp.711-720.

Galea, E.R., Gwynne, S., Blackshields, D., Lawrence, P.J., Filippidis, L., 2001. Predicting the evacuation performance of passenger ships using computer simulation. *Proceedings of the 9th International Fire Science and Engineering Conference: Interflam 2001*, Edinburgh, Scotland, Interscience Communications Ltd: London, Vol. 2, pp.853-864, ISBN 0 95323129 1 (vol2).

Galea, E.R., Gwynne, S., Lawrence, P.J., Filippidis, L., Blackshields, D., Cooney, D., 2004. *buildingEXODUS V4.0 User Guide and Technical Manual*. University of Greenwich.

Galea E.R., Wang, Z., Veeraswamy, A., Jia, F., Lawrence, P., Ewer, J., 2008. Coupled Fire/Evacuation Analysis of the Station Nightclub Fire. *Proceedings of 9th IAFSS Symposium*, Karlsruhe, Germany, pp.465-476, doi:10.3801/IAFSS.FSS.9-465.

Gibson, J.J., 1977. *The theory of affordances. In Perceiving, Acting, and Knowing: Toward and Ecological Psychology*, Shaw R, Bransford J (eds)., Lawrence Erlbaum: Hillsdale, NJ, pp.67-82.

Gibson, J.J., 1979. *The Ecological Approach to Visual Perception*. Houghton Mifflin: Boston.

Grosshandler, W., Bryner, N., Madrzykowski. D., Kuntz, K., 2005. *Report of the Technical Investigation of The Station Nightclub Fire*. NIST NCSTAR 2: volume I.

Grosshandler, W., Bryner, N., Madrzykowski. D., Kuntz, K., 2005. *Report of the Technical Investigation of The Station Nightclub Fire: Appendices*. NIST NCSTAR 2: volume II.

Gwynne, S., Boswell, D.L., 2009. Pre-evacuation data collected from a mid-rise evacuation exercise. *Fire Protection Engineering*, 19(1), pp.5-29, doi:10.1177/1042391508095093.

Gwynne, S., Galea, E.R., Owen, M., Lawrence, P.J., 1999a. Escape as a Social Response. Society of Fire Protection Engineers: Bethesda, MD, USA.

Gwynne, S., Galea, E.R., Owen, M., Lawrence, P.J., Filippidis, L., 1999b. A Review of the Methodologies Used in the Computer Simulation of Evacuation from the Built Environment. *Building and Environment*, 34(6), pp.741-749.

Gwynne, S., Galea, E.R., Owen, M., Lawrence, P. J., Filippidis, L., 2000. Adaptive decision-making in buildingEXODUS in response to exit congestion. *Fire Safety Science – Proceedings of the Sixth International Symposium*, University of Poitiers, France, 1999, pp.1041-1052.

Gwynne, S., Galea, E.R., Lawrence, P.J., Filippidis, L., 2001. Simulating occupant interaction with smoke using buildingEXODUS. *Proceedings of the 2nd International Symposium on Human Behaviour in Fire*, Boston, USA, Interscience Communications Ltd: London, pp.101-110, ISBN 0953231267.

Gwynne, S., 2000. *The Introduction of Adaptive Social Decision-Making in the Mathematical Modelling of Egress Behaviour*. PhD Thesis, School of Computing & Mathematical Sciences, the University of Greenwich: Greenwich, England.

Hajibabai, L., Delavar, M., Malek, M., Frank, A., 2007. Agent-Based Simulation of Spatial Cognition and Wayfinding in Building Fire Emergency Evacuation. LNG&C, *Geomatics Solutions for Disaster Management*, pp.255-270.

Health and Safety (Safety Signs and Signals) Regulations 1996 (SI No. 1996/341), The Stationery Office: London, ISBN 978-0-11-054093-1.

Helbing, D., Molnár, P., 1995. Social force model for pedestrian dynamics. *Physical Review E*, 51(5), pp.4282-4286.

Helbing, D., Farkas, I., Molnár, P., Vicsek,T., 2002. Simulating of Pedestrian Crowds in Normal and Evacuation Situations. *Pedestrian and Evacuation Dynamics*, Schreckenberg, M. and Sharma, S.D. (eds.), Springer: Berlin, pp.21-58, ISBN 978-3-540-42690-5.

Helbing, D., 1991. A mathematical model for the behavior of pedestrians. *Behavioral Science*, 36(4), pp.298-310, doi: 10.1002/bs.3830360405.

Henson, D.B., 1993. *Visual fields*, Oxford University Press: Oxford, ISBN 0-19-262361-3.

Heskestad, A.W., Meland, O.J., 1998. Determination of Evacuation Times as a Function of Occupant and Building Characteristics and Performance of Evacuation Measures. *Proceedings of the 1st International Symposium on Human Behaviour in Fire*, Belfast, UK, pp.673-680.

Hoffmann, N.A., Henson, D.A., 1997. Simulating Transient Evacuation and Pedestrian Movements in Stations. *Proceedings of the International Conference on Mass Transit*, International Technical Conferences, UK.

Hoogendoorn, S.P., Daamen, W., Bovy, P.H.L., 2003. Microscopic Pedestrian Traffic Data Collection and Analysis by Walking Experiments: Behaviour at Bottlenecks. *Proceedings of the 2nd International Conference on Pedestrian and Evacuation Dynamics*, Galea ER (ed.), CMS Press: Greenwich, UK, pp.341-354, ISBN 1-904521-08-8.

Husted, B., Carlsson, J., Göransson, U., 2004. Visibility Through Inhomogeneous Smoke Using CFD. *Proceedings of the 10th International Fire Science and Engineering Conference: Interflam 2004*, Edinburgh, Scotland, pp.697-702.

International Standards Office, 1984. *ISO 3864:1984 Safety colours and safety signs*, ISO: Geneva.

International Standards Office, 1987. *ISO 6309:1987 Fire protection – Safety signs*, ISO: Geneva.

International Standards Office, 1999. *ISO/TR 13387-8:1999 Fire safety engineering -- Part 8: Life safety -- Occupant behaviour, location and condition*, ISO: Geneva.

International Standards Office, 2002. *ISO 3864-1:2002 Graphical symbols -- Safety colours and safety signs -- Part 1: Design principles for safety signs in workplaces and public areas*, ISO: Geneva.

International Standards Office, 2003. *ISO 7010:2003 Graphical symbols – Safety colours and safety signs – Safety signs used in workplaces and public areas*, ISO: Geneva.

International Standards Office, 2004. *ISO 16069:2004 Graphical Symbols – Safety signs – Safety Way Guidance Systems*, ISO: Geneva.

International Standards Office, 2009. *ISO/TR 16738:2009 Fire-safety engineering -- Technical information on methods for evaluating behaviour and movement of people*, ISO: Geneva.

James Lee Witt Associates, LLC, 2004. *Cook County Administration Building Fire Review*.

Jiang, H., Gwynne, S., Galea, E.R., Lawrence, P., Jia, F., Ingason, H., 2003. The use of Evacuation simulation, Fire Simulation and Experimental Data in Forensic Fire Analysis. *Proceedings of the 2nd International Conference on Pedestrian and Evacuation Dynamics*, Galea ER (ed.), CMS Press: Greenwich, UK, pp.89-100, ISBN 1-904521-08-8.

Jin, T., Yamada T., 1985. Irritating effects from fire smoke on visibility. *Fire Science and Technology*, 5(1), pp.79-90.

Jin, T., Yamada T., 1989. Experimental Study of Human Behavior in Smoke Filled Corridors. *Fire Safety Science – Proceedings of the Second International Symposium*, Tokyo, Japan, pp.511-519, ISBN 0-89116-864-8.

Jin, T., 1978. Visibility through fire smoke. *Journal of Fire and Flammability*, 9, pp.135-155.

Jin, T., 1997. Studies on human behavior and tenability in fire smoke. *Fire Safety Science – Proceedings of the Fifth International Symposium*, Melbourne, Australia, pp.3-21, ISBN 4-9900625-5-5.

Jin, T., 2008. Visibility and human behavior in fire smoke. *The SFPE Handbook of Fire Protection Engineering (4th edn)*, NFPA: Quincy, MA 02269 USA, pp.2/54-2/66, ISBN 0-87765-821-8.

Joe Cappucio, P.E., 2000. PathFinger: A Computer-Based, Timed Egress Simulation. *Fire Protection Engineering*, No. 8, pp.11-12.

Kendik, E., 1986. Methods of Design for Means of Egress: Towards a Quantitative comparison of National Code Requirements. *Fire Safety Science - Proceedings of the First International Symposium*, Maryland, USA, 1985, pp.497-511.

Keßel, A., Klüpfel, H., Meyer-König, T., Schreckenberg, M., 2002. A Concept for Coupling Empirical Data and Microscopic Simulation of Pedestrian Flows. *International conference on Monitoring and Management of visitor flows in recreational and protected areas*, Wien, Austria, 2002, pp.199-204.

Ketchell, N., Cole, S., Webber, D., 1993. The EGRESS Code for Human Movement and Behaviour in Emergency Evacuations. Proceedings of The International Conference on Engineering for Crowd Safety, London.

Ketchell, N., 2002. *A Technical Summary of the AEA EGRESS Code*.

Kholshevnikov, V.V., Shields, T.J., Boyce, K.E., Samoshin, D.A., 2007. Recent developments in pedestrian flow theory and research in Russia. *Fire Safety Journal*, 43(2), pp.108-118.

Kinsey, M.J., Lawrence, P.J., Galea, E.R., 2010. Stairs or Lifts? - A Study of Human Factors associated with Lift/Elevator usage during Evacuations using an online Survey. *Proceedings of the 5th International Conference on Pedestrian and Evacuation Dynamics*, NIST, Maryland, USA, pp.627-636.

Kisko, T. M., Francis, R.L., 1985. EVACNET+: A Computer Program to Determine Optimal Building Evacuation Plans. *Fire Safety Journal*, 9(2), pp.211-220.

Kisko, T. M., Francis, R. L.,1986. Evacnet+, A Building Evacuation Computer Program. *Fire Technology*, 22(1), pp.75-76.

Kisko, T. M., Francis, R. L., Nobel, C. R., 1998. *EVACNET4 USER'S GUIDE*.

Klüpfel,H., Meyer-König, T., 2003. Characteristics of the PedGo Software for Crowd Movement and Egress Simulation. *Proceedings of the 2nd International Conference on Pedestrian and Evacuation Dynamics*, Galea ER (ed.), CMS Press: Greenwich, UK, pp.331-340, ISBN 1-904521-08-8.

Korhonen, T., Hostikka, S., 2008. *Fire Dynamics Simulator with Evacuation FDS+Evac, version 5. Technical Reference and User's Guide*.

Korhonen, T., Hostikka, S., Keski-Rahkonen, O., 2005. A Proposal for the Goals and New Techniques of Modelling Pedestrian Evacuation in Fires. *Fire Safety Science – Proceedings of the Eighth International Symposium*, Tsinghua University, Beijing, China, pp.557-567.

Korhonen, T., Hostikka, S., Heliövaara, S., Ehtamo, H., Matikainen, K., 2007. Integration of an agent based evacuation simulation and the state-of-the-art fire simulation. *Proceedings of the 7th Asia–Oceania Symposium on Fire Science & Technology*, Hong Kong.

Kuligowski, E.D., Peacock, R.D., 2005. A Review of Building Evacuation Models. NIST, Technical Note 1471.

Kuligowski E.D., 2008. Computer evacuation models for buildings. *The SFPE Handbook of Fire Protection Engineering (4th edn)*, NFPA: Quincy, MA 02269 USA, pp.3/456-3/478, ISBN 0-87765-821-8.

Levenberg, K., 1944. A method for the solution of certain problems in least squares. *The Quarterly of Applied Mathematics*, Vol. 2, pp.164-168.

Levin, B.M., 1989. Exitt - A Simulation Model Of Occupant Decisions And Actions In Residential Fires. *Fire Safety Science - Proceedings of the Second International Symposium*, 2, pp.561-570.

Lo, S.M., Fang, Z., 2000. A Spatial-Grid Evacuation Model for Buildings. *Journal of Fire Sciences*, 18(5), pp.376-394.

Lo, S.M., Fang, Z., Lin, P., Zhi, G.S., 2004. An evacuation model: the SGEM package. *Fire Safety Journal*, 39(3), pp.169-190.

Lo, S.M., Huang, H.C., Wang, P., Yuen, K.K., 2006. A game theory based exit selection model for evacuation. *Fire Safety Journal*, 41(5), pp.364-369.

Marquardt, D., 1963. An algorithm for least-squares estimation of nonlinear parameters. *SIAM Journal on Applied Mathematics*, 11(2), pp.431-441.

McClintock, T., Shields, T.J., Reinhardt-Rutland, A.H., Leslie, J.C., 2001. A behavioural solution to the learned irrelevance of emergency exit signage. *Proceedings of the 2nd International Symposium on Human Behaviour in Fire*, MIT, Boston, USA, Interscience Communications Ltd: London, pp.23-33, ISBN 0953231267.

McGrattan, K., Hostikka, S., Floyd, J., Baum, H., Rehm, R., 2008. Fire Dynamics Simulator (Version 5) Technical Reference Guide Volume 1: Mathematical Model. NIST Special Publication 1018-5, Gaithersburg, MA.

McGrattan, K., Klein, B., Hostikka, S., and Floyd, J., 2008. Fire Dynamics Simulator (Version 5) User's Guide. NIST Special Publication 1019-5, Gaithersburg, MA.

Morley, F.J.J., Cobbett, A.M., 1997. An evaluation of the comprehensibility of graphical exit signs for passenger aircraft, Phases 1 & 2. COA report No.9706, Cranfield University.

Moussaïd, M., Helbing, D., Garnier, S., Johansson, A., Combe, M., Theraulaz, G., 2009. Experimental study of the behavioral mechanisms underlying self-organization in human crowds. *Proceedings of the Royal Society B*, 276, pp.2755–2762.

Newman, D.G., Locke, H.A., 1998. Simulation Versus Code Methods for Predicting Airport Evacuation. *Proceedings of the 1st International Symposium on Human Behaviour in Fire*, Belfast, UK.

National Fire Protection Association, 1997. Life Safety Code Handbook. NFPA: Quincy, MA.

Nilsson, D., 2009. *Exit choice in fire emergencies - Influencing choice of exit with flashing lights*. PhD Thesis, Department of Fire Safety Engineering and Systems Safety, Lund University: Lund, Sweden.

O'Neill, M.J., 1991. Effects of Signage and Floor Plan Configuration on Wayfinding Accuracy. *Environment and Behavior*, 23(5), pp.553-574.

Olenick, S.M., Carpenter, D.J., 2003. An Updated International Survey of Computer Models for Fire and Smoke. *Journal of Fire Protection Engineering*, 13(2), pp.87-110.

Oleszkiewicz, I., 1994. The Concept and Practice of Performance-Based Building Regulations. National Research Council of Canada: Ottawa.

Owen, M., Galea, E.R., Lawrence, P. J., 1996. The Exodus Evacuation Model Applied To Building Evacuation Scenarios. *Journal of Fire Protection Engineering*, 8(2), pp.65-86.

Owen, M., Galea, E.R., Lawrence, P. J., 1997. Advanced Occupant Behavioural Features of the buildingEXODUS Evacuation Model. *Fire Safety Science – Proceedings of the Fifth International Symposium*, Melbourne, Australia, pp.795-806, ISBN 4-9900625-5-5.

Ozel, F., 1985. A Stochastic Computer Simulation of the Behavior of People in Fires: An Environmental Cognitive Approach. *Proceedings of the International Conference on Building Use and Safety Technology*.

Ozel, F., 1987. The computer model BGRAF: a cognitive approach to emergency egress simulation. *PhD Thesis*, The University of Michigan.

Ozel, F., 1988. Calibration and Validation of Computer Model BGRAF. Safety in the Built Environment, Sime J, Spon FN (eds), E & FN Spon: London, pp.75-86, ISBN 0-419-14480-3.

Ozel, F., 1991. Simulation of Processes in Buildings as a Factor in the Object Representation of Built Environments. *Proceedings of Building Simulation '91*, Nice, France, the International Building Performance Simulation Association, pp.250-256.

Ozel, F., 1993. Computer Simulation of Behavior in Spaces. *Environmental Simulation: Research and Policy Issues*, R.W.Marans & D. Stokols (Eds.), Plenum Press: New York, pp.191-204.

Ozel, F., 2001. Time pressure and stress as a factor during emergency egress. *Safety Science*, 38(2), pp.95-107.

Pan, X., 2006. *Computational Modeling of Human and Social Behaviors for Emergency Egress Analysis*. PhD Thesis, Stanford University.

Passini, R., 1992. *Wayfinding in Architecture*, Van Nostrand Reinhold: New York, ISBN 0-442-01095-8.

Pauls, J., 1984. The Movement of People in Buildings and Design Solutions for Means of Egress. *Fire Technology*, 20(1), pp.27-46.

Pauls, J., 1990. Building Evacuation Research Findings And Recommendations. *Fires And Human Behaviour (2nd Edition)*, Ed. Canter, D., Fulton, pp.15-30.

Paulsen, T., 1994. The effect of escape route information on mobility and way finding under smoke logged conditions. *Fire Safety Science – Proceedings of the Fourth International Symposium*, Ottawa, Canada, pp.693–704, ISBN 1-886279-00-4.

Poon, L.S., Beck, V.R., 1994. Evacsim: Simulation Model Of Occupants With Behavioural Attributes In Emergency Evacuation Of High Rise Buildings. *Proceedings Of Fourth International Symposium On Fire Safety Science*, pp.681-692, ISBN 1-886279-00-4.

Poon, L.S., 1985. Numerical Modelling Of Human Behaviour During Egress In Multi-Storey Office Building Fires Using Evacsim-Some Validation Studies. *Proceeding For The International Conference On Fire Science And Engineering*, pp.163-174, ISBN 0951632078.

Predtechenskii, V. M., & Milinskii, A. I., 1975. Standardization of Evacuation. Roytman, M. Ya. *Principles of Fire Safety Standards for Building Construction*, Amerind Publishing Co., Pvt. Ltd.: New Delhi.

Predtechenskii, V. M., & Milinskii, A. I., 1978. Planning for Foot Traffic Flow in Buildings. Published For The National Bureau Of Standards, Translated From The Russian Publication Which Appeared In 1969, Stroizdat Publishers, Moscow, 1969, Amerind Publishing Co., Pvt. Ltd.: New Delhi.

Proulx, G., Fahy, R.F., 2008. Human Behavior and Evacuation Movement in Smoke. ASHRAE Transactions, 114(2), pp.159-165.

Purser, D.A., 1989. Modelling time to incapacitation and death from toxic and physical hazards in aircraft fires. *AGARD Conference proceedings*, No. 476, Aircraft Fire Safety, pp.41/1-41/13, ISBN 92-835-0529-8.

Purser, D.A., 1995. Toxicity Assessment of Combustion Products. *The SFPE Handbook of Fire Protection Engineering (2nd edn)*, NFPA: Quincy, MA 02269 USA, pp.2/85–2/146, ISBN 0-87765-354-2.

Purser, D.A., 1996. Behavioural impairment in smoke environment. *Toxicology*, 115(1-3), pp.25-40.

Purser, D.A., 2001. Human Tenability: The Technical Basis for Performance Based Fire Regulations. United Engineering Foundation Conference. San Diego, CA, pp.88-129.

Purser, D.A., 2003. ASET And RSET: Addressing Some Issues In Relation To Occupant Behaviour And Tenability. *Fire Safety Science – Proceedings of the Seventh International Symposium*, Worcester, Massachusetts, USA, pp.91-102, ISBN 0-9545348-0-8.

Purser, D.A., 2008. Assessment of Hazards to Occupants from Smoke, Toxic Gases, and Heat. *The SFPE Handbook of Fire Protection Engineering (4th edn)*, NFPA: Quincy, MA 02269 USA, pp.2/96-2/193, ISBN 0-87765-821-8.

Raubal, M., 2001. *Agent-based simulation of human wayfinding: A perceptual model for unfamiliar buildings*. PhD Thesis, the Vienna University of Technology: Wien, Germany.

Rea, M.S., Clark, F.R.S., Ouellette, M.J., 1985. Photometric and psychophysical measurements of exit signs through smoke. National Research Council of Canada publication NRCC 24627, Ottawa.

Regulatory Reform (Fire Safety) Order 2005 (SI No. 2005/1541), The Stationery Office: London, ISBN 0-11-072945-5.

Reisser-Weston, E., 1996. Simulating Human Behaviour in Emergency Situations. RINA, International Conference of Escape, Fire, and Rescue.

Rhodes, N., Hoffmann, N.A., 2000. Modelling Newcastle's International Centre for Life for Fire Safety. *Building Performance*, Issue 3, Winter 2000/1, BEPAC.

Rubini, P.A., Zhang, Q., Moss, J.B., 2007. Simulation of visibility in smoke laden environments. *Proceedings of the 11th International Conference on Fire Science and Engineering, InterFlam 2007*, Royal Holloway College, University of London, UK, Interscience Communications Ltd: London, Vol. 1, pp.479-490, ISBN 978-0-9556548-0-0 (set).

Safety Signs Regulations 1980 (SI No. 1980/1471), The Stationery Office: London.

Santos, G., Aguirre, B. E., 2004. A Critical Review of Emergency Evacuation Simulation Models. *Proceeding of Conference Building Occupant Movement During Fire Emergencies*, Gaithersburg, Maryland, USA.

Schneider, V., 2001. Application of the individual-based evacuation model ASERI in designing safety concepts. *Proceedings of the 2nd International Symposium on Human Behaviour in Fire*, MIT, Boston, USA, Interscience Communications Ltd: London, pp.41-51, ISBN 0953231267.

Schneider, V., 2003. Simulating the Evacuation of Large Assembly Occupancies. *Proceedings of the 2nd International Conference on Pedestrian and Evacuation Dynamics*, Galea ER (ed.), CMS Press: Greenwich, UK, pp.319-330, ISBN 1-904521-08-8.

Schneider, V., 2004. Modelling of human response and behaviour in complex surroundings. *Proceedings of the 3rd International Symposium on Human Behaviour in Fire*, Belfast, UK, Interscience Communications Ltd: London, pp.387-397, ISBN 0-9541216-6-X.

Schneider, V., Könnecke, R., 2008. Egress Route Choice Modelling - Concepts and Applications. *Proceedings of the 4th International Conference on Pedestrian and Evacuation Dynamics*, Wuppertal, Germany, pp.619-625.

Shestopal, V.O., 2003. Computer Modelling of Merging Pedestrian Traffic. *Proceedings of the 2nd International Conference on Pedestrian and Evacuation Dynamics*, Galea ER (ed.), CMS Press: Greenwich, UK, pp.395-403, ISBN 1-904521-08-8.

Shields, T.J., Boyce, K.E., 2000. A study of evacuation from large retail stores. *Fire Safety Journal*, 35(1), pp.25-49, doi:10.1016/S0379-7112(00)00013-8.

Shil, N., Lin, C., Yang, C., 2000. A virtual-reality-based feasibility study of evacuation time compared to the traditional calculation method. *Fire Safety Journal*, 34(4), pp.377-391.

Sime, J.D., 1984. *Escape Behaviour In Fire: 'Panic' Or Affiliation?* PhD Thesis, Department of Psychology, University of Surrey: Surry, England.

Sime, J.D., 1985. Movement toward the familiar: person and place affiliation in a fire entrapment setting. *Environment and Behavior*, 17(6), pp.697-724, doi:10.1177/0013916585176003.

Sime, J.D., 2001. An occupant response shelter escape time (ORSET) model. *Safety Science*, 38(2), pp.109-125.

Simulex User Guide <Virtual Environment> 5.8, 2007.

Sixsmith, A., Sixsmith, J., Canter, D., 1988. When is a door not a door? A study of evacuation route identification in a large shopping mall. *Safety in the Built Environment*, Sime J, Spon FN (eds), E & FN Spon: London, pp.62-74, ISBN 0-419-14480-3.

Stahl, F.I., 1982. BFIRES-II: A behavior based computer simulation of emergency egress during fires. *Fire Technology*, 18(1), pp.49-65, doi: 10.1007/BF02993488.

STEPS 4.0 User manual, 2010.

Still, G.K., 2000. *Crowd Dynamics*. PhD Thesis, Department of Mathematics, University of Warwick.

Sychta, Z., 1997. Contrast attenuation coefficient as a parameter enabling determination of range of visibility in smoke. *Fire and Materials*, 21(5), pp.205-211.

The Scandinavian Star Disaster of 7 April 1990. Main Report, NOR 1991:1E. PDC: Aurskog, Norway, ISBN 82-583-0236-1.

Thompsons, P., Marchant, E., 1994. Simulex: Developing New Computing Modelling Techniques For Evaluation. *Proceedings Of The Fourth International Symposium On Fire Safety Science*, Ed: Kashiwagi, T., pp.613-624.

Thompsons, P., Marchant, E., 1995. A Computer Model for the Evacuation of Large Building Populations. *Fire Safety Journal*, 24(2), pp.131-148.

Thompsons, P., Marchant, E.,1995. Testing and application of the computer model 'SIMULEX'. *Fire Safety Journal*, 24(2), pp.149-166.

Thompsons, P., Marchant, E., 1996. Modelling Evacuation In Multi-Storey Buildings With Simulex. *Fire Engineers Journal*, pp.7-11.

Thompson, P.A., 1994. *Developing new techniques for modelling crowd movement*. PhD Thesis, University of Edinburgh.

PEDROUTE Version 5 Manual, 2000.

Veeraswamy, A., Lawrence, P.J., Galea, E.R., 2009. Implementation of Cognitive Mapping, Spatial Representation and Wayfinding Behaviours of People within Evacuation Modelling Tools. *Proceedings of the 4th International Symposium on Human Behaviour in Fire*, Robinson College, Cambridge, UK, Interscience Communications Ltd: London, pp.501-512, ISBN 978-0-9556548-3-1.

Voeltzel, A., 2002. Compared analysis of the Mont Blanc Tunnel and the Tauern Tunnel Fires. Report of WG6 of PIARC (World Road Association).

Wall, J.M., Waterson, N.P., 2002. Predicting evacuation times – a comparison of the STEPS simulation approach with NFPA 130. *Fire Command Studies*, 1(1).

Wang, C., Zhang, P., Zhou, Z., Lo, S., Liu, M., 2006. Investigation and Analysis on Human's Wayfinding Decision Behavior Towards Exit Signs in Evacuation Process. *Proceedings of the*

2006 International Symposium on Safety Science and Technology, Changsha, China, pp.399-402.

Was J., Gudowski B., Matuszyk, P.J., 2006. Social Distances Model of Pedestrian Dynamics. In: *El Yacoubi Chopard B*., Bandini S. (eds.) ACRI 2006 LNCS, Springer: Heidelberg, Vol. 4173, pp.492-501.

Watts, J.M., 1994. Performance-based codes. *Fire Technology*, 30(4), pp.385-386.

Watts, J.M., 1996. Fire safety objectives. *Fire Technology*, 32(1), pp.1-2.

Weinspach, P.M., Gundlach, J., Klingelhofer, H.G., Ries, R., Schneider, U., 1997. Analysis Of The Fire On April 11th, 1996. Recommendations And Consequences For Düsseldorf Rhein-Ruhr-Airport, Staatskanzlei Nordrhein-Wstfalen, Mannesmannufer 1 A, 40190 Düsseldorf, Germany.

Weisman, G., 1981. Evaluating architectural legibility: wayfinding in the built environment. *Environment and Behavior*, 13(2), pp.189-204.

Weisman, G., 1985. Orientation, Path Finding, and Architectural Legibility: a Review and Theoretical Integration. *Proceedings of the International Conference on Building Use and Safety Technology*, NIBS, pp.9-15.

Werner, E.B., 1991. *Manual of Visual Fields*, Churchill Livingstone: New York, ISBN 0-44-308689-3.

Wong, L.T., Lo, K.C., 2007. Experimental study on visibility of exit signs in buildings. *Building and Environment*, 42(4), pp.1836-1842.

Wood, P., 1972. The Behaviour of People in Fires. Fire Research Note No.953, Fire Research Station

Wright, M.S., Cook, G.K., Webber, G.M.B., 2001. Visibility of four exit signs and two exit door markings in smoke as gauged by twenty people. *Proceedings of the 2nd International Symposium on Human Behaviour in Fire*, MIT, Boston, USA, Interscience Communications Ltd: London, pp.147-158, ISBN 0953231267.

Wright, M.S., Cook, G.K., Webber, G.M.B., 2001. The effects of smoke on people's walking Speeds using overhead lighting and Wayguidance provision. *Proceedings of the 2nd International Symposium on Human Behaviour in Fire*, MIT, Boston, USA, Interscience Communications Ltd: London, pp.275-284, ISBN 0953231267.

Xie, H., Filippidis, L., Galea E.R., Gwynne, S., Blackshields, D., Lawrence, P.J., 2005. Experimental study and theoretical analysis of signage legibility distances as a function of observation angle. *Pedestrian and Evacuation Dynamics 2005*, N. Waldau, P. Gattermann (eds.), Springer: Berlin, pp.131-143, ISBN 978-3-540-47062-5.

Xie, H., Filippidis, L., Gwynne, S., Galea, E.R., Blackshields, D., Lawrence, P.J., 2007. Signage Legibility Distances as a Function of Observation Angle. *Journal of Fire Protection Engineering*, 17(1), pp.41–64, doi:10.1177/1042391507064025.

Xie, H., Filippidis, L., Galea, E.R., Blackshields, D., Lawrence, P.J., 2009. Experimental Study of the Effectiveness of Emergency Signage. *Proceedings of the 4th International Symposium on Human Behaviour in Fire*, Robinson College, Cambridge, UK, Interscience Communications Ltd: London, pp.289-300, ISBN 978-0-9556548-3-1.

Zhang, Q., Rubini, P., 2009. Simulation of perceived visibility in smoke laden environment. *Proceedings of the 4th International Symposium on Human Behaviour in Fire*, Robinson College, Cambridge, UK, Interscience Communications Ltd: London, pp.267-278, ISBN 978-0-9556548-3-1.

Zhang, Q., Rubini, P., 2010. Quantitative validation of simulated visibility in smoke laden environments. *Proceedings of the 12th International Fire Science & Engineering Conference, Interflam 2010*, University of Nottingham, UK, Interscience Communications Ltd: London, Vol. 1, pp.825-835, ISBN 978-0-9541216-5-5 (Vol.1).

Appendix A1: Announcement to Participants

The Fire Safety Engineering Group of the University of Greenwich would like to thank you for coming and assisting us with this trial experiment. Each of you will be involved in a single trial. The performance of these trials will allow us to better understand human interaction with their surroundings and the consequences of this interaction.

As part of this trial programme, we will ask you to perform a simple task on your own. A member of staff will lead you up to a certain location in this building. At a given time, you will be asked to **navigate around** the environment, move along the corridor and **find your way out** of the corridor as best as you can. You should assume that you have been told to evacuate the building. However, there will be no sound alarm. You should NOT attempt to sound the alarm at any point during the trial. You are free to select **any** route available unless prevented from doing so.

You should move as quickly as possible, but you should limit your movement to **walking**. If a participant is observed to be running, his/her performance will be discounted. You should continue the task until informed otherwise, at which point the trial is over. During this task, you should experience no more difficulties than you might experience in your normal movement around a building.

Your movement will be monitored at several places by fixed cameras, in order to best capture the data produced by your participation and enable us to gain a better understanding of your performance. You will be provided with head gear fitted with a recording device. This is a light weight device, similar to a bicycle hat. A member of staff will assist you in donning the head gear and you will be able to familiarise yourself with wearing it. For example, you can walk for a short while with it on prior to the trial taking place. If you feel uncomfortable in any way, the member of staff will help you adjust it.

On completion of the trial, you will return here. We will give you a brief interview directly relating to your experiences during the trial. Please remember in answering the interview questions it is important to understand that ***there are no right or wrong answers***; we are simply trying to understand your actions. The interview will also be recorded on audio.

We will keep all of the recorded material for research purposes; some of the material may be used and shown in public fora. However, your anonymity is assured and your personal details will not be linked to the information collected.

The entire process should take approximately 20 minutes of your time. However, you may be requested to wait prior to the start of the trial or prior to completing the questionnaire and interview. Once the interview is completed you will be free to go. If at any time you wish to withdraw from the trial, please inform a member of staff and you will be free to leave.

Finally, we request that you do not discuss the trial with any of your fellow participants throughout. You can also find the information in more detail in the handout briefing.

Once again, thank you for your assistance in this experimental programme.

Appendix A2: Briefing to Participants

The Fire Safety Engineering Group of the University of Greenwich would like to thank you in advance for assisting us with this trial experiment. We are performing a number of trials to better understand human interaction with their surroundings. This understanding will assist us in improving safety levels within buildings.

THE TASK:

- As part of this trial programme, we will ask you to perform a simple task. During this task, you should be presented with no more difficulties than you might experience in moving around a building in normal use.
- When the time comes, you will don a small piece of head gear and you will then be led up two flights of stairs to a pre-arranged location.
- There will be no alarm sounded to start or stop the task. You should NOT attempt to sound the alarm at any point during the trial. Please follow the instructions provided by our member of staff during the trial.
- At a given time, you will be asked to **navigate around the environment in which you are placed, move along the corridor** and **find your way out of the corridor as best you can**. You are free to **select a route** unless it appears unavailable (e.g. there is furniture preventing clear access to it) or if prevented from using the route by a member of staff.
- You should assume that you have been told to evacuate the building. You should move as quickly as possible, but you should limit your movement to **walking**. If a participant is observed to be running, his/her performance will be discounted.
- If for any reason you meet another person other than FSEG staff during the trial, please stop where you are until instructed to continue.
- You should perform the task until a member of staff indicates the end of the task. The trial itself should only take a few minutes.

THE MEASUREMENTS:

- During this activity you will be monitored and your actions will be recorded on video.
- We will keep the film of your recorded information for research purposes and some of the video footage may be shown in public fora. However, your personal details will not be linked to the information collected.
- The film will be deleted after a short period of time.
- No access to the film record is given to any third party. For the same reason, we do not offer you a copy of the video on completion in order to better control the distribution of this material.
- As mentioned above, you will also be provided with head gear fitted with a recording device. A member of staff will assist you in putting on the head gear and instruct you in its use, although you are not expected to perform any complex actions during the trial.
- After initially donning the head gear, you should walk for a while to familiarise yourself with wearing it. If the head gear affects your visual field and/or head movement, or is uncomfortable in anyway, please tell the member of staff, and we will try to adjust and reduce the influence.
- The equipment has been designed to collect information which will help us enormously in our understanding of your performance.

THE INTERVIEWS:

- On completion of the task, you will be brought back here where you will remain until called to attend a short interview.
- A member of staff will ask you some questions relating to your experiences during the trial. To prevent missing important information that you might provide, we will use audio recording device.
- We will keep the audio records for research purposes; some of these recordings may be used in public fora; no access to the recordings is given to any third party; and the recording will be deleted after a short period of time.
- The entire process should take approximately 20 minutes of your time. However, you may be requested to wait prior to the start of the trial or prior to completing the questionnaire/interview.
- Once the interview is complete you will be free to go.

RIGHT TO WITHDRAW:

- Your previous agreement to take part in this set of trials does not affect your right to withdraw from the trial at any stage.
- If at any time you wish to withdraw from the trial, please inform a member of staff and you will be free to leave.
- If you wish to withdraw from the trial, we will erase all records relating to your performance including video, audio and registration information at the first practical moment.

CONFIDENTIALITY:

- We request that you do not discuss the trial with any of your fellow participants throughout.

THANKS:

- Your assistance in this experimental programme is greatly appreciated.

I have read the information sheet about this study and understand what will be going on during the trial. I also know that I will be recorded on both video tape and audio tape during the trial for research purposes. I declare that I am able to perform the tasks outlined above. I fully agree to take part in this study.

Signature of the participant: ___________________ Date: ____________________

Appendix A3: Questionnaire (Participant Version)

- *Please do not read your questionnaire until the interviewer tells you.*
- *Please only read one question at a time as we go through it.*

Dear volunteer,

Thank you for participating in this trial. Your time and effort have contributed to the success of this trial, the results of which will have a direct impact on the future safety of buildings in which we spend much of our time. In order for us to benefit fully from the results produced, we would like you to complete a brief background survey and take part in a short interview. Some parts of this interview will be recorded to aid future analysis. It should take approximately fifteen to twenty minutes to complete.

For each of the questions, could you please provide an appropriate answer(s). A member of staff will assist you during the interview. If you have any queries, please feel free to ask.

Your anonymity is assured during this procedure, in relation to any associated published document. Your name will not appear anywhere on the questionnaire or in the results presented.

Once again, thank you for your time and effort.

Background Survey

Participant No. [ ]

Please complete this background survey by ticking the appropriate answers.

1. Please tick your gender, age, and identify the status of your vision:

   Gender: ☐ Male ☐ Female

   Age: ☐ Under 20 ☐ 20-30 ☐ 30-40
   ☐ 40-50 ☐ 50-60 ☐ 60-70
   ☐ Over 70

   Vision: ☐ Uncorrected vision.
   Corrected vision by …
   ☐ Glasses or contact lens all of the time.
   ☐ Glasses or contact lens for reading and/or long distance.

2. How did you become aware of these trials?
   ☐ Newspaper ☐ Internet
   ☐ Word of mouth ☐ Other, please indicate ______________________________

3. Were you aware of the internal structure of this building prior to the trial?
   ☐ Not at all.
   ☐ Partly; e.g. you had used seen the interior before today and/or you may be an occasional user of the building.
   ☐ Completely familiar; e.g. you are a regular user of the building.

4. Have you ever participated in any evacuation drill before (e.g. a fire drill at work or at school)?
   ☐ Yes. (How long ago? __________________________)
   ☐ No.

5. Have you ever experienced a real emergency evacuation before?
   ☐ Yes. (How long ago? __________________________)
   ☐ No.

■ *Thank you for filling in this survey, please hand in this sheet when you attend the interview.*

<u>Section One</u>

*In answering the questions in this questionnaire it is important to note that there are **no right** or **wrong answers**. We are simply trying to understand your actions. Please answer the following questions.*

1. Did any technical recording equipment **interfere** with your progress during the trial?
   (a) No.
   (b) A little.
   (c) Significant interference.

   *If you chose **(b)** or **(c)**, please specify the nature of the interference and what equipment interfered with your progress.*

2. The route adopted by you during the trial is marked on **the map** provided. Can you talk us through the route you took, describing why you selected the route? It may be helpful to break your account into segments based on the decisions that you made. In particular can you describe:

   - *what **factors** influenced your route selection,*
   - *what **actions** you took during your movement and*
   - *other general comments about your **experiences** during the trial.*

   Please provide us with as much detail as possible you may also tag on the map to help explain your actions. Your description of these events will be recorded in order for detailed analysis to take place. Please use the labels to indicate any important locations. For example, you started from door D3, and approached area A8…

Section Two

Given the route adopted during the trial, please answer the following questions. Each of the questions relates to a point along the route that you adopted and attempt to examine the reasons influencing the decisions made. For the following questions, you may select more than one alternative. If more than one answer is selected please indicate which had the most impact upon your decision. The interviewer will read out the questions to you and then, once you have understood the question, will prompt you for your response.

1. The first decision point presented to you was as you left the starting point moving from A8, approaching the junction at A7 (as indicated by the interviewer). You chose to go left/right in the trial. ***When and where did you decide to move in this direction?***

   a. In the grey area, before you could see A6 and/or A10.
   b. In A7, after you saw A6 and/or A10.
   c. None of the above.

   Please also mark ***the site of your decision*** *on the map as accurately as possible* ***with one dot only***.

2. Following Question 1, there were two choices available to you: turning left and turning right. You chose to [go left/go right]. ***Can you indicate why you chose this direction and which of the following influenced your decision?*** **Please read through these options carefully and indicate to the interviewer which of the statements are correct. Please ask if you require further information relating to the options.**

   a. You were unaware of any other routes available other than the one that you selected.
   b. You were more familiar with the route selected than any of the others available.
   c. You had decided on your choice of direction before investigating for other routes available.
   d. The route you selected seemed shorter than any other routes available.
   e. The environmental conditions and/or the architectural configuration encouraged you to move in the direction selected.
      If you chose this, please indicate which of the following factors influenced you:
      - The lighting levels;
      - The presence of furniture, notice boards, etc.;
      - The design of the corridor/room;
      - Others, *please specify*.
   f. You saw an exit sign and decided to follow the information in it.
   g. The route you took seemed appropriate; the decision to adopt this route was then reinforced by the presence of an exit sign.
   h. If none of the previous statements applied, or there were other influences / comments that were not mentioned above, please indicate.

   If you ***selected more than one option****, can you now look at the options that you selected and choose which of them had the* ***most influence*** *over your decision.*

3. According to the route that you adopted, you [turned left/turned right] and then moved along this section of the corridor (A6/A10). ***Again, can you indicate why you continued along this route and which of the following options influenced your decision?*** **Please read through these options carefully and indicate to the interviewer which of them are correct. Please ask if you require further information relating to the options.**

a. You were unaware of any other routes available other than the one that you selected.
b. You were more familiar with the route selected than any of the others available.
c. You had decided on your choice of direction before investigating for other routes available and intended to stick by this decision.
d. The environmental conditions and/or the architectural configuration encouraged you to move in the direction selected.

   If you this, please indicate which of the following factors influenced you:
   - The lighting levels;
   - The presence of furniture, notice boards, etc.;
   - The design of the corridor/room;
   - Others, *please specify*.

e. You saw an exit sign and decided to follow the information in it.
f. The direction you took seemed appropriate; this decision was then reinforced by the presence of an exit sign.
g. If none of the previous statements applied, or there were other influences / comments that were not mentioned above, please indicate.

*If you **selected more than one option**, can you now look at the options that you selected and choose which of them had the **most influence** over your decision.*

4. You had to make a decision as you arrived at A2/A12. You chose to [continue on in the same direction/go left to a side door /go right to a side door]. ***When and where did you make this decision?***

   a. Before you reached the grey area (i.e. before reaching this exit).
   b. In the grey area, once you could see the two alternatives.
   c. None of the above.

   *Please also mark **the location of your decision** on the map as accurately as possible **with one dot only**.*

5. Following Question 4, there were two choices available to you at the grey area: continue on in the same direction (D1/D5) or [turn left/ right] into a side door (D2/D4). ***Can you indicate why you chose this door/route and which of the following influenced your decision? Please read through these options carefully and indicate to me which of them are correct. Please ask if you require further information relating to the options.***

   a. You were unaware of any other exits/routes available other than the one that you selected.
   b. You were more familiar with the exit/route selected than any of the others available.
   c. You had decided on your choice of direction before investigating for other routes available and intended to stick by this decision.
   d. Given that you had started moving in this direction, it seemed that you should continue on in this direction.
   e. The environmental conditions and/or the architectural configuration encouraged you to move in the direction chosen.

      If you this, please indicate which of the following factors influenced you:
      - The lighting levels;
      - The presence of furniture, notice boards, etc.;
      - The design of the corridor/room;
      - Others, *please specify*.

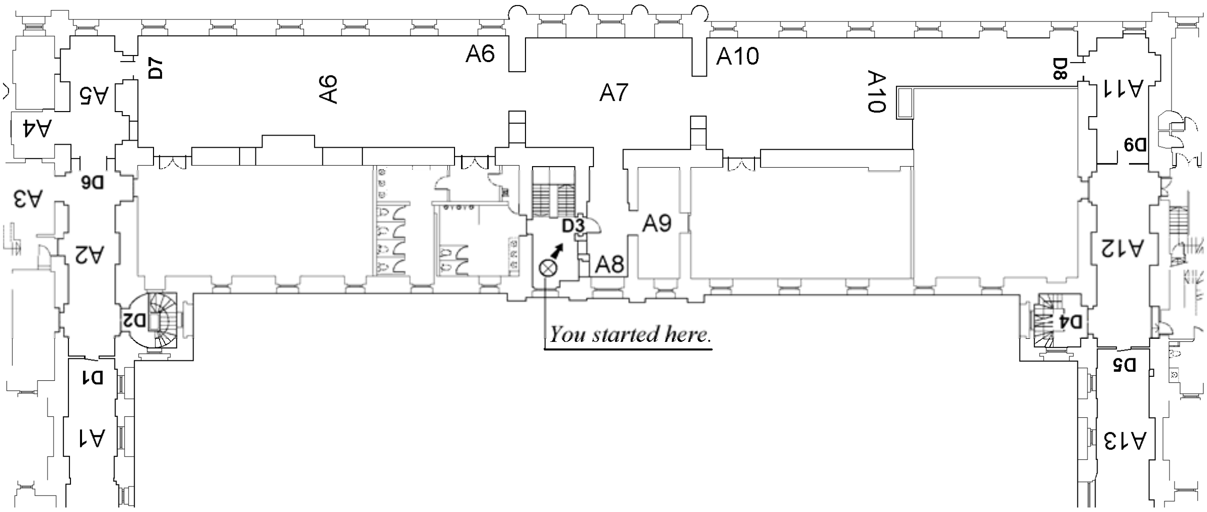
   f. You saw an exit sign and decided to follow the information in it.

g. The direction you took seemed appropriate; this decision was then reinforced by the presence of an exit sign.
h. If none of the previous statements applied, or there were other influences / comments that were not mentioned above, please indicate.

*If you **selected more than one option**, can you now look at the options that you selected and choose which of them had the **most influence** over your decision.*

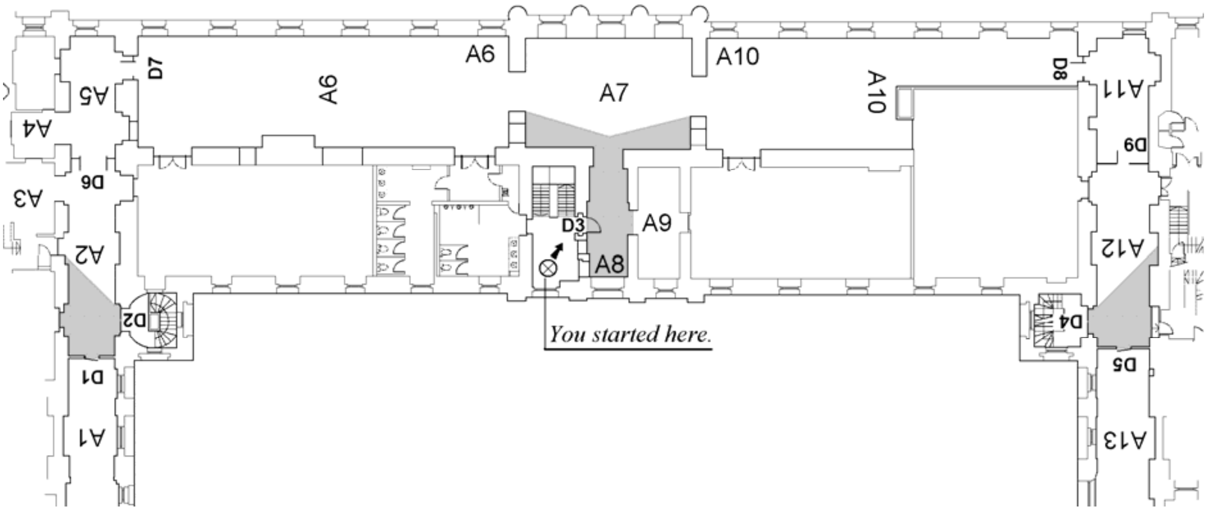
Section Three

A member of staff will play back the video filmed by the camera on your head during your movement along the corridor. Please carefully observe the playback of the video, and then answer the questions posed to you. Please keep in mind that the video playback is only used to help remind you of the process of the trial. When you answer the questions, you should base your ***replies upon your recollection of your experiences*** *during the trial, rather than what you currently see during the video playback.*



Side A: The layout plan of the first floor in the Queen Anne Court.

Note: *You may ask for help about the direction and the orientation of the diagram if you have difficulty in understanding the map.*



Side B: The layout plan of the first floor in the Queen Anne Court.

Note: *You may ask for help about the direction and the orientation of the diagram if you have difficulty in understanding the map.*

Appendix A4: Questionnaire (Interviewer Version)

Questionnaire and Data Sheet Section to be taken into interview

Boxed comments indicate actions

Section One

Interviewer should read all text unless indicated.

*In answering the questions in the questionnaire it is important to note that there are **no right** or **wrong answers**. We are simply trying to understand your actions. Please answer the following questions.*

Interviewer uses the answer sheet to record the response to questions.

1. Did any recording equipment interfere with your progress during the trial?
   (a) No.
   (b) A little.
   (c) Significant interference.

   *If you chose (**b**) or (**c**), please specify the nature of the interference and what equipment interfered with your progress.* ***Do you have any additional comments?***

Mark Answer

(1) Present map (Side A) – Mark route according to P1's record.

(2) Switch on recording device – Announce: Participant No., Interviewer, Date.

2. The route adopted by you during the trial is marked on the map provided. Can you talk us through the route you took, describing why you selected the route? It may be helpful to break your account into segments based on the decisions that you made. In particular can you describe:

   - *what **factors** influenced your route selection,*
   - *what **actions** you took during your movement and*
   - *other general comments about your **experiences** during the trial.*

   ► *Please provide us with as much detail as possible you may also tag on the map to help explain your actions. Your description of these events will be recorded in order for detailed analysis to take place. Please use the labels to indicate any important locations. For example, you started from door D3, and approached area A8…*

Mark comments if required.

Section Two

Given the route adopted during the trial, please answer the following questions. Each of the questions relates to a point along the route that you adopted and attempt to examine the reasons influencing the decisions made. For the following questions, you may select more than one alternative. If more than one answer is selected please indicate which had the most impact upon your decision. I will read out the questions to you and then, once you have understood the question, will prompt you for your response.

Interviewer uses the answer sheet to record the response to questions.

(3) Present the map (B) – turn over map.

1. The first decision point presented to you was as you left the starting point moving from A8, approaching the junction at A7 **Indicate**. You chose to go left/right in the trial. ***When and where did you decide to move in this direction?***

   (a) In the grey area, before you could see A6 and/or A10.
   (b) In A7, after you saw A6 and/or A10.
   (c) None of the above.

Mark Answer

Please also mark ***the site of your decision*** *on the map as accurately as possible* ***with one dot only****.*

Hand participant a pencil and encourage to produce a *dot*, not a cross.

2. Following Question 1, there were two choices available to you: turning left and turning right. You chose to [go left/go right]. ***Can you indicate why you chose this direction and which of the following influenced your decision? Please read through these options carefully and indicate to me which of them are correct. Please ask if you require further information relating to the options.***

Allow participant to read through options alone and indicate selections.

   (a) You were unaware of any other routes available other than the one that you selected.
   (b) You were more familiar with the route selected than any of the others available.
   (c) You had decided on your choice of direction before investigating for other routes available.
   (d) The route you selected seemed shorter than any other routes available.
   (e) The environmental conditions and/or the architectural configuration encouraged you to move in the direction selected.
   If you chose this, please indicate which of the following factors influenced you:
   - The lighting levels;
   - The presence of furniture, notice boards, etc.;
   - The design of the corridor/room;
   - Others, *please specify*.

   (f) You saw an exit sign and decided to follow the information in it.
   (g) The route you took seemed appropriate; the decision to adopt this route was then reinforced by the presence of an exit sign.
   (h) If none of the previous statements applied, or there were other influences / comments that were not mentioned above, please indicate.

Confirm the selected statements with the participant. If more than one option was selected, read back the options selected to the participant in full and ask which of them had the most influence over their decisions.

You selected the following options **Read list***; can you now look at the options that you selected and choose which of them had the most influence over your decision.*

Mark Answer

(4) If (*f*) or (*g*) is selected, request them to mark location of the sign with a *cross*.

Rotate Map

3. According to the route that you adopted, you [turned left/turned right] and then moved along this section of the corridor **Indicate** (A6/A10). ***Again, can you indicate why you continued along this route and which of the following options influenced your decision? Please read through these options carefully and indicate to me which of them are correct. Please ask if you require further information relating to the options.***

Allow participant to read through options alone and indicate selections.

(a) You were unaware of any other routes available other than the one that you selected.
(b) You were more familiar with the route selected than any of the others available.
(c) You had decided on your choice of direction before investigating for other routes available and intended to stick by this decision.
(d) The environmental conditions and/or the architectural configuration encouraged you to move in the direction selected.
If you chose this, please indicate which of the following factors influenced you:
- The lighting levels;
- The presence of furniture, notice boards, etc.;
- The design of the corridor/room;
- Others, *please specify*.

(e) You saw an exit sign and decided to follow the information in it.
(f) The route you took seemed appropriate; the decision to adopt this route was then reinforced by the presence of an exit sign.
(g) If none of the previous statements applied, or there were other influences/ comments that were not mentioned above, please indicate.

Confirm the selected statements with the participant. If more than one option was selected, read back the options selected to the participant in full and ask which of them had the most influence over their decisions.

You selected the following options **Read list***; can you now look at the options that you selected and choose which of them had the most influence over your decision.*

Mark Answer

(5) If (*e*) or (*f*) is selected, request them to mark location of the sign with a *cross*.

Rotate Map

4. You had to make a decision as you arrived at A2/A12 **Indicate**. You chose to [continue on in the same direction/go left to a side door /go right to a side door]. ***When and where did you make this decision?***

   (a) Before you reached the grey area (i.e. before reaching this exit).
   (b) In the grey area, once you could see the two alternatives.
   (c) None of the above.

Mark Answer

Please also mark ***the location of your decision*** *on the map as accurately as possible with one dot only.*

Hand them a pencil and encourage them to produce a *dot* and not a cross.

5. Following Question 4, there were two choices available to you at the grey area: continue on in the same direction (D1/D5) and [turning left/ turning right] to a side door (D2/D4) **Indicate**. ***Can you indicate why you chose this door/route and which of the following influenced your decision? Please read through these options carefully and indicate to me which of them are correct. Please ask if you require further information relating to the options.***

Allow participant to read through options alone and indicate selections

   (a) You were unaware of any other exits/routes available other than the one that you selected.
   (b) You were more familiar with the exit/route selected than any of the others available.
   (c) You had decided on your choice of direction before investigating for other routes available and intended to stick by this decision.
   (d) Given that you had started moving in this direction, it seemed that you should continue on in this direction.
   (e) The environmental conditions and/or the architectural configuration encouraged you to move in the direction chosen.
   If you chose this, please indicate which of the following factors influenced you:
   - The lighting levels;
   - The presence of furniture, notice boards, etc.;
   - The design of the corridor/room;
   - Others, *please specify*.

   (f) You saw an exit sign and decided to follow the information in it.
   (g) The direction you took seemed appropriate; this decision was then reinforced by the presence of an exit sign.
   (h) If none of the previous statements applied, or there were other influences / comments that were not mentioned above, please indicate.

Confirm the selected statements with the participant. If more than one option was selected, read back the options selected to the participant in full and ask which of them had the most influence over their decisions.

If you selected more than one option, can you now look at the options that you selected and choose which of them had the most influence over your decision.

Mark Answer

(6) If (*f*) or (*g*) is selected, request them to mark location of the sign with a *cross*.

■ The end of **Section Two**. Go to **Section Three.**

Section Three

I will play back the video produced by the camera on your head during your movement along the corridor and will pause the camera at key points during your trial in order to gather additional information. Please carefully observe the playback of the video, and then answer the questions posed to you. Please keep in mind that the video playback is only used to help remind you of the process of the trial. When you answer the questions, you should base your ***replies upon your recollection of your experiences*** *during the trial, rather than what you currently see during the video playback.*

(7) Present the map (B)

Play back the entire trial at normal speed before rewinding the footage to the start and slowing advancing to particular points.

Rotate map as interview continues.

Interviewer uses the answer sheet to record the response to questions.

Replay entire footage to capture additional behaviour, not previously addressed.

■ The end of **Section Three**.

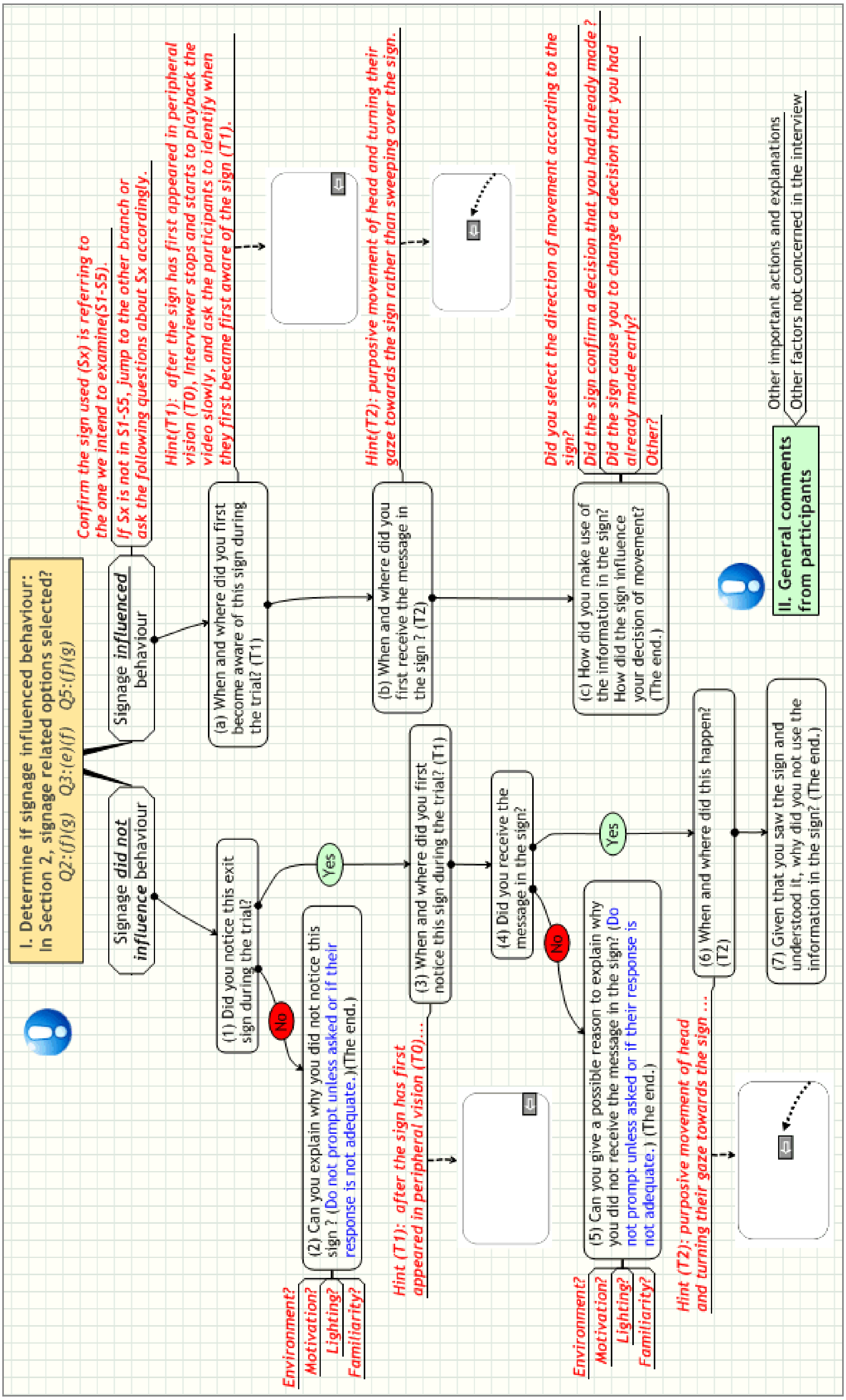


Figure 1: Questions break down

Appendix A5: Risk Assessment as Part of Application for Ethical Approval

Hazard: Stairs ***Risk Level (High, medium, low):*** Low ***Who Is At Risk?*** Participants ***Measures provided to reduce risks:*** Although the experiment does not require participants to navigate stairs, it does require them to climb two flights of stairs to get to the starting point on the first floor of the test building. This will be addressed when recruiting volunteers. Also, a member of staff will always warn participants to mind the stairs when leading them to the starting point.
Hazard: Stress ***Risk Level (High, medium, low):*** Low ***Who Is At Risk?*** Participants ***Measures provided to reduce risks:*** The participant task may exert a psychological stress on them, not only because participants have to perform the task as quickly as possible to simulate an evacuation scenario, but also because some of them are unfamiliar with the built environment. As a result, some participants may choose to run, increasing the likelihood of a minor accident, such as tripping over. And some may be lost in the building or stuck in a closed enclosure. This issue is addressed by two measures. Firstly, the briefing given to participants prior to the trials will clearly explain that they should move quickly but without running. Secondly, a member of staff will follow participants and warn them when they are moving too fast. If they get lost or suck, the staff member will approach from behind to solve the circumstances.
Hazard: Portable video recording device ***Risk Level (High, medium, low):*** Low ***Who Is At Risk?*** Participants ***Measures provided to reduce risks:*** Participants will be carrying a set of portable video recording device during the trials. The device is composed of a head mounted min camera with wires connected to a portable video recorder. It is possible, though highly unlikely, that participants could get entangled in the wires. To avoid this issue, a member of staff will help participants put on the device and make sure that they feel comfortable with it before starting the trials. Participants will be helped by staff member to put off the device. Participants are not required to operate the recording device.
Hazard: Equipment ***Risk Level (High, medium, low):*** Low ***Who Is At Risk?*** Staff ***Measures provided to reduce risks:*** The experiment requires staff to operate some video recording devices which will be plugged into the power mains. They may be liable to electric shock if they operate incorrectly. To avoid this issue, all equipment will be put through electrical safety test to make sure they meet all current safety standards. Training will also be given to staff members involved.

Appendix A6: Ethical Approval for Research

the UNIVERSITY of GREENWICH

Direct Line 020 8331 8587
Direct Fax 01634 883447
Email L.T.Spencer@gre.ac.uk
Our Ref 034-15 LS//REC/apprvlet
Date 7th June 2004

Mr Hui Xie
37 Ridge Close,
Thamesmead
London
SE 28 0HX

Dear Mr Xie

Research Ethics Committee - Application No. 034-15

'Analysis of the effectiveness of building signage during circulation and movement"

I am pleased to inform you that your proposal with the above title was approved by the Research Ethics Committee on 7th June 2004 . The following points were identified.

- The poster will need to state clearly that participants will need to be able to navigate stairs,
- On page 2 of subject information sheet omit first bullet point (right to withdraw) so that it is clearer in its layout..

I am advised by the Committee to remind you of the following points:

1. Your responsibility to notify the REC immediately of any information received by you, or of which you become aware, which would cast doubt upon, or alter, any information contained in the original application, or a later amendment, submitted to the REC and/or which would raise questions about the safety and/or continued conduct of the research.
2. The need to comply with the Data Protection Act
3. The need to comply, throughout the conduct of the study, with good research practice standards
4. The need to refer proposed amendments to the protocol to the REC for further review and to obtain REC approval thereto prior to implementation (except only in cases of emergency when the welfare of the subject is paramount).

THE QUEEN'S ANNIVERSARY PRIZES
FOR HIGHER AND FURTHER EDUCATION
2000 & 2002

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