

Architectural cue model in evacuation simulation for underground space design

Citation for published version (APA):

Sun, C. (2009). *Architectural cue model in evacuation simulation for underground space design*. [Phd Thesis 2 (Research NOT TU/e / Graduation TU/e), Built Environment]. Technische Universiteit Eindhoven.
<https://doi.org/10.6100/IR640314>

DOI:

[10.6100/IR640314](https://doi.org/10.6100/IR640314)

Document status and date:

Published: 01/01/2009

Document Version:

Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
- The final author version and the galley proof are versions of the publication after peer review.
- The final published version features the final layout of the paper including the volume, issue and page numbers.

[Link to publication](#)

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license above, please follow below link for the End User Agreement:

www.tue.nl/taverne

Take down policy

If you believe that this document breaches copyright please contact us at:

openaccess@tue.nl

providing details and we will investigate your claim.

Architectural Cue Model in Evacuation Simulation for Underground Space Design

PROEFSCHRIFT

ter verkrijging van de graad van doctor aan de
Technische Universiteit Eindhoven, op gezag van de
Rector Magnificus, prof.dr.ir. C.J. van Duijn, voor een
commissie aangewezen door het College voor
Promoties in het openbaar te verdedigen
op donderdag 22 januari 2009 om 16.00 uur

door

Chengyu Sun

geboren te Shanghai, China

Dit proefschrift is goedgekeurd door de promotor:

prof.dr.ir. B. de Vries

Copromotor:
dr. L. Xu MArch

Copyright © 2009 C. Sun
Technische Universiteit Eindhoven,
Faculteit Bouwkunde, Design Systems Group

Cover design: Tekenstudio, Faculteit Bouwkunde
Printed by: The Eindhoven University of Technology Press Facilities

BOUWSTENEN 132

ISBN 978-90-6814-615-8
NUR-code: 648

Preface

It was in the summer of year 1995 that I encountered the first-person shooter game DOOM for the first time. The feeling during fighting the demons in the fictional spaces is so touching that I noticed my body sometimes moving simultaneously with the Doomguy in the game, although I can only perceive the virtual space through a 14-inch screen. Two years later I entered College of Architectural and Urban Planning in Tongji University and started my architecture professional education.

In the end of year 2004, I have an opportunity to talk with Prof. Xu and Prof. Tang on one of the interesting research topics in their project to investigate the human being's evacuation behavior in the built environment, which is funded by the National Nature and Science Funds in China. This topic is about how the evacuee searches his route to the safety in the underground space. We all believe that abstract architectural space can influence the evacuees' behavior. However, a systematic investigation on abstract architectural space is challenging. Although I hadn't played DOOM for a long time, I notice that my experiences in the cyber architectural spaces urge me to start the research in this topic with the virtual reality (VR) technologies. In my idea, the virtual reality just gives architect an opportunity to investigate the abstract architectural space without other interferences existing in the real world.

Fortunately, I started this research topic as my PhD project from year 2005 supervised by Prof. de Vries, who has a lot of experiences in the VR-based researches. After I upgrade the virtual reality technologies in this research for several times, I do think that these technologies are promising. However, sometimes I have to answer the serious question from my colleagues in Tongji University, "Is the research based on the behaviors observed in a virtual environment valid?" My answer is somewhat tricky. I prepare the latest first-person shooter game in their PCs. After they have been absorbed in the game and experienced moving their own bodies simultaneously with the role in the game, they always can answer the question by themselves positively.

Frankly, I do not think the current VR technologies have already been perfect in all kinds of human behavior researches. As revealed by the several VR technologies tried in this research, the researcher should customize his own VR facility and adopt some other techniques if necessary according to the features of his own behavioral research. In this research, as one kind of VR technologies, a special CAVE system is customized and used as the most suitable technique among all the experimental psychology techniques according to the features of the abstract architectural space, which is interpreted as the architectural cue in this thesis.

In brief, as an architect of the post-DOOM generation, I believe that the developing VR technologies must be able to help the architects both in their designs and in their researches.

Acknowledgments

This research and thesis couldn't be done without the help of many persons.

I would like to express my gratitude to my supervisor Prof. Bauke de Vries. Although the two-week discussion through Yahoo Messenger was very hard and time consuming, he continuously guided my research for three years. Whenever I was stuck or confused, he always could help me to find some way out. These discussions saved in the text files reflected the research track clearly and were the treasure of my PhD project.

I wish to thank my colleagues in Tongji University, Prof. Xu and Prof. Tang. They could always provide critical comments on my work and the discussions with them were very heuristic. Additionally, Prof. Xu partially funded my work through his own project. Prof. Tang helped me a lot in the construction of the VR facilities in Tongji University.

I would like to also thank my colleagues in Design System group of TU/e. The thesis was written during my visit funded by the group in Eindhoven. Jan Dijkstra gave me a lot of help on the crucial part of this research (the Conjoint Analysis experiment). Sjoerd Buma always supported me on the ICT problems. The other colleagues Henri Achten, Joran Jessurun, Aant van der Zee, Jacob Beetz, Qunli Chen, Yuzhong Lin, Remco Niemeijer, Rona Vreenegoor, and Kymo Slager always brought me sparkling ideas and supported me in all my presentations. Notably, Marlyn Aretz was always helpful to me in all the detailed things for my stay.

If there was anything exciting besides the thesis during my visit, it was to meet the professors in different fields related to my research. Their feedbacks on my presentation were always helpful. The talk with Prof. Timmermans invoked my further investigation on the variable levels. The talk with Prof. Hoogendoorn invoked my study on the red-car-and-blue-car question. Later, Prof. Arentze helped me to understand this question by his clear explanation. Prof. Helsloot gave me the opportunity to learn how his PhD student, Margrethe Kobes, did the evacuation experiment in both the real environment and the virtual environment.

Besides all the above colleagues in Tongji University and TU/e, some talented students also helped me during this research. As a mathematical master student, Ms. Juanjuan Cai taught me a lot about the usage of SPSS. With an architectural education background, I think sometimes I seemed to be a bad student to her. Without her patience, my work in SPSS was impossible. Moreover, I would like to thank Ms. Weiyang Yu and Ms. Xijia Wang. They were the experiment assistants in all my experiments. They spent hundreds of hours to keep the experiment going on with hundreds of participants. Notably, Ms. Weiyang Yu also devoted her talent on programming to my work. Several algorithms in the computer-based prototype were based on her ideas. Furthermore, I would thank all the students participating in the experiments in Tongji University.

Last but not least, I thank my parents and my wife. In the past four years, they always supported me and let me work in the lab during all holidays.

Table of Contents

| | |
|-------------------------------------------------------------------------|-------------|
| PREFACE | III |
| ACKNOWLEDGMENTS | IV |
| TABLE OF CONTENTS | V |
| LIST OF FIGURES | VIII |
| LIST OF TABLES | X |
| 1 INTRODUCTION | 1 |
| 1.1 MOTIVATION | 2 |
| 1.1.1 Demand from Real-World Projects | 2 |
| 1.1.2 Architectural Way to Improve Evacuation Evaluation..... | 2 |
| 1.1.3 Architectural Cue in Evacuee’s Route Searching..... | 3 |
| 1.1.4 Research Field and Questions | 5 |
| 1.2 METHOD | 6 |
| 1.3 CONTRIBUTIONS..... | 8 |
| 1.4 DISSERTATION OVERVIEW | 8 |
| 2 REVIEWS ON CUE-BASED EVACUATION RESEARCHES | 11 |
| 2.1 CUE-BASED EVACUATION..... | 12 |
| 2.1.1 Evacuation as a Type of Way-finding | 12 |
| 2.1.2 From Perceived Light to Meaningful Cues | 19 |
| 2.1.3 Various Visual Cues..... | 23 |
| 2.1.4 Convinced or Confused by Cues | 31 |
| 2.1.5 Decision Making with Cues | 33 |
| 2.1.6 Summary..... | 35 |
| 2.2 EVACUATING IN COMPLEX PUBLIC UNDERGROUND SPACE DESIGN | 36 |
| 2.2.1 Nature of Space Design..... | 36 |
| 2.2.2 Limited Architectural Cue | 37 |
| 2.2.3 Limited Strategy | 38 |
| 2.2.4 Proper Decision Making Model..... | 38 |
| 2.2.5 Summary..... | 39 |
| 2.3 MODELING ARCHITECTURAL CUES IN EVACUATION SIMULATION | 40 |
| 2.3.1 A Brief Introduction on Evacuation Behavior Researches | 40 |
| 2.3.2 Architectural Cue Modeling in 36 Existing Evacuation Models | 41 |
| 2.3.3 Summary..... | 46 |
| 2.4 MEASURING HUMAN PREFERENCES SYSTEMATICALLY | 47 |
| 2.4.1 Environmental Psychology Research Issues | 47 |
| 2.4.2 Development from Paper-and-pencil to Virtual Reality..... | 49 |
| 2.4.3 Measurement of Preference in Virtual Reality | 54 |
| 2.4.4 Summary..... | 58 |
| 2.5 SUMMARY OF THE CHAPTER..... | 58 |
| 3 DEVELOPMENT OF THE COMPUTATIONAL MODEL | 59 |
| 3.1 AIMS | 60 |
| 3.1.1 Process Explained in a Computational Model..... | 60 |
| 3.1.2 Design Evaluation with an Architect-oriented Criterion..... | 61 |
| 3.1.3 Summary..... | 61 |

| | | |
|----------|----------------------------------------------------------------|------------|
| 3.2 | SURVEY OF LOCAL ARCHITECTURAL CUES | 62 |
| 3.2.1 | <i>Overview</i> | 62 |
| 3.2.2 | <i>Procedure</i> | 62 |
| 3.2.3 | <i>Conclusions</i> | 63 |
| 3.3 | OBSERVATION ON THE EVACUATION BEHAVIOR | 66 |
| 3.3.1 | <i>Overview</i> | 66 |
| 3.3.2 | <i>Design of the Observation Experiment</i> | 66 |
| 3.3.3 | <i>Procedure</i> | 68 |
| 3.3.4 | <i>Analysis</i> | 69 |
| 3.3.5 | <i>Conclusions</i> | 82 |
| 3.4 | FRAMEWORK OF THE MODEL | 86 |
| 3.4.1 | <i>Overview</i> | 86 |
| 3.4.2 | <i>“Start Evacuation”</i> | 88 |
| 3.4.3 | <i>“Check Arrival Cues”</i> | 89 |
| 3.4.4 | <i>“See”</i> | 90 |
| 3.4.5 | <i>“Choose”</i> | 91 |
| 3.4.6 | <i>“Move”</i> | 92 |
| 3.4.7 | <i>Summary</i> | 92 |
| 3.5 | ESTIMATION OF THE PREFERENCE PREDICTION FUNCTION | 93 |
| 3.5.1 | <i>Overview</i> | 93 |
| 3.5.2 | <i>Design of the Estimation Experiment</i> | 93 |
| 3.5.3 | <i>Procedure</i> | 104 |
| 3.5.4 | <i>Analysis</i> | 105 |
| 3.5.5 | <i>Conclusions</i> | 113 |
| 3.6 | PROTOTYPE OF THE MODEL | 116 |
| 3.6.1 | <i>Overview</i> | 116 |
| 3.6.2 | <i>Demonstration on Route Searching Process</i> | 118 |
| 3.6.3 | <i>Demonstration on LEEI Evaluation</i> | 125 |
| 3.6.4 | <i>Conclusions</i> | 127 |
| 3.7 | SUMMARY OF THE CHAPTER | 128 |
| 4 | VALIDATIONS | 129 |
| 4.1 | DISCUSSION ON THE VALIDATION METHOD | 130 |
| 4.1.1 | <i>Indirect Reference</i> | 130 |
| 4.1.2 | <i>Comparative Method in Validation</i> | 131 |
| 4.2 | COMPARING WITH THE LOCAL NEAREST-EXIT MODEL | 133 |
| 4.3 | COMPARING WITH THE GLOBAL NEAREST-EXIT MODEL | 135 |
| 4.3.1 | <i>Overview</i> | 135 |
| 4.3.2 | <i>Analysis</i> | 136 |
| 4.3.3 | <i>Conclusions</i> | 144 |
| 4.4 | SUMMARY OF THE CHAPTER | 144 |
| 5 | CONCLUSIONS | 145 |
| 5.1 | SUMMARIES OF THE THESIS | 146 |
| 5.2 | DISCUSSIONS ON THE NEW DESIGN GUIDELINES | 147 |
| 5.2.1 | <i>Visual Accessibility & Distance Accessibility</i> | 147 |
| 5.2.2 | <i>Psychological Scale & Physical Scale</i> | 148 |
| 5.3 | FUTURE DIRECTION | 149 |
| | REFERENCES | 151 |
| | APPENDIXES | 161 |

| | |
|--------------------------------------------------------------------------|------------|
| APPENDIX A ARCHITECTURAL CUE USAGE IN 36 EXISTING EVACUATION MODELS..... | 162 |
| APPENDIX B QUESTIONNAIRE ON LOCAL ARCHITECTURAL CUES | 167 |
| APPENDIX C DESIGN OF THE CAVE PLATFORM..... | 169 |
| APPENDIX D VIRTUAL UNDERGROUND SITE IN THE OBSERVATION EXPERIMENT | 170 |
| APPENDIX E DOCUMENT OF THE PROTOTYPE PROGRAM | 172 |
| <i>E.1 Preparing Space Model File in AutoCAD.....</i> | <i>172</i> |
| <i>E.2 Operating the User Interface.....</i> | <i>173</i> |
| <i>E.3 Reading the Output Files.....</i> | <i>175</i> |
| <i>E.4 Understanding the Image-Based-Recognition Algorithms.....</i> | <i>176</i> |
| APPENDIX F STATISTIC REPORTS | 182 |
| <i>F.1 Report of the Cue Pair D-D.....</i> | <i>182</i> |
| <i>F.2 Report of the Cue Pair S-S.....</i> | <i>184</i> |
| <i>F.3 Report of the Cue Pair E-E.....</i> | <i>186</i> |
| <i>F.4 Report of the Cue Pair S-E</i> | <i>188</i> |
| APPENDIX G ESTIMATED CURVES OF THE RATIO-PROBABILITY DISTRIBUTIONS | 191 |
| <i>G.1 Estimations for the line function.....</i> | <i>191</i> |
| <i>G.2 Estimations for the growth function</i> | <i>195</i> |
| AUTHOR INDEX | 197 |
| DUTCH SUMMARY | 200 |
| CURRICULUM VITAE | 201 |

List of Figures

| | |
|----------------------------------------------------------------------------------------------|-----|
| Figure 1.1-1 Research fields | 5 |
| Figure 1.2-1 Research methods..... | 6 |
| Figure 2.1-1 Evacuation process..... | 18 |
| Figure 2.1-2 Visual perception process for the visual cue | 21 |
| Figure 2.1-3 Conflict between the redundant visual cues..... | 33 |
| Figure 3.3-1 Virtual scene in the observation experiment | 68 |
| Figure 3.3-2 B1 Plan with traces..... | 70 |
| Figure 3.3-3 B2 Plan with traces..... | 70 |
| Figure 3.3-4 B3 Plan with traces..... | 70 |
| Figure 3.3-5 Traces from Starting Point I | 71 |
| Figure 3.3-6 Traces from Starting Point II..... | 72 |
| Figure 3.3-7 Traces from Starting Point III..... | 72 |
| Figure 3.3-8 Traces from Starting Point IV | 73 |
| Figure 3.3-9 Traces from Starting Point V..... | 74 |
| Figure 3.3-10 Traces from Starting Point VI | 75 |
| Figure 3.3-11 Traces from Starting Point VII | 76 |
| Figure 3.3-12 Traces from Starting Point VIII..... | 77 |
| Figure 3.3-13 Traces from Starting Point IX | 78 |
| Figure 3.3-14 Traces from Starting Point X..... | 78 |
| Figure 3.3-15 Traces from Starting Point XI | 79 |
| Figure 3.3-16 Traces from Starting Point XII..... | 80 |
| Figure 3.3-17 Traces from Starting Point XIII..... | 81 |
| Figure 3.3-18 Traces from Starting Point XIV | 81 |
| Figure 3.4-1 Model framework..... | 87 |
| Figure 3.4-2 View in the underground space design..... | 89 |
| Figure 3.4-3 Pixel array of the artificial vision..... | 89 |
| Figure 3.5-1 Attributes A1, A2, D, W, and H of Doorway Entrance | 94 |
| Figure 3.5-2 Attributes A1, A2, D, W, and H of Up Stair | 94 |
| Figure 3.5-3 Attributes A1, A2, D, W, and H of Exit..... | 94 |
| Figure 3.5-4 Distorted human view of the scene No.39 in Stair-Exit set | 101 |
| Figure 3.5-5 Interactive interface for the experiment | 103 |
| Figure 3.5-6 Relationship of the attributes and the probabilities in the S-E set | 107 |
| Figure 3.5-7 Relationship of the attributes and the probabilities in the D-D set | 107 |
| Figure 3.5-8 Relationship of the attributes and the probabilities in the E-E set | 108 |
| Figure 3.5-9 Relationship of the attributes and the probabilities in the S-S set..... | 108 |
| Figure 3.5-10 Ratio-Probability distribution of RatioD in S-S pair with line function | 111 |
| Figure 3.5-11 Ratio-Probability distribution of RatioD in S-S pair with growth function..... | 113 |
| Figure 3.6-1 User interface of SpaceSensor..... | 116 |
| Figure 3.6-2 Plan of B2 level with one route..... | 118 |
| Figure 3.6-3 Plan of B1 level with one route..... | 118 |
| Figure 3.6-4 Plan of B2 level with multi-routes | 126 |
| Figure 4.1-1 Two levels of comparisons in validation..... | 131 |
| Figure 4.3-1 Simulated traces from Starting Point I | 137 |
| Figure 4.3-2 Simulated traces from Starting Point II..... | 137 |
| Figure 4.3-3 Simulated traces from Starting Point III | 138 |
| Figure 4.3-4 Simulated traces from Starting Point IV | 138 |
| Figure 4.3-5 Simulated traces from Starting Point V..... | 139 |

| | |
|--------------------------------------------------------------|-----|
| Figure 4.3-6 Simulated traces from Starting Point VI | 139 |
| Figure 4.3-7 Simulated traces from Starting Point VII | 140 |
| Figure 4.3-8 Simulated traces from Starting Point VIII..... | 140 |
| Figure 4.3-9 Simulated traces from Starting Point IX | 141 |
| Figure 4.3-10 Simulated traces from Starting Point X..... | 141 |
| Figure 4.3-11 Simulated traces from Starting Point XI | 142 |
| Figure 4.3-12 Simulated traces from Starting Point XII..... | 142 |
| Figure 4.3-13 Simulated traces from Starting Point XIII..... | 143 |
| Figure 4.3-14 Simulated traces from Starting Point XIV..... | 143 |
| Figure 5.2-1 Modifications on the exits and stairs..... | 148 |

List of Tables

| | |
|---------------------------------------------------------------------------------------------------|-----|
| Table 2.3-1 Classification according to architectural cue modeling | 42 |
| Table 3.2-1 Ranked local architectural cues in underground spaces | 63 |
| Table 3.2-2 Evacuee’s consideration on the architectural elements..... | 64 |
| Table 3.3-1 Distribution of the starting points | 67 |
| Table 3.3-2 Choice(s) in Starting Point II | 71 |
| Table 3.3-3 Choice(s) in Starting Point III..... | 72 |
| Table 3.3-4 Choice(s) in Starting Point IV..... | 73 |
| Table 3.3-5 Choice(s) in Starting Point V | 74 |
| Table 3.3-6 Choice(s) in Starting Point VII | 76 |
| Table 3.3-7 Choice(s) in Starting Point VIII | 77 |
| Table 3.3-8 Choice(s) in Starting Point IX..... | 78 |
| Table 3.3-9 Choice(s) in Starting Point X..... | 78 |
| Table 3.3-10 Choice(s) in Starting Point XI..... | 79 |
| Table 3.3-11 Choice(s) in Starting Point XII | 80 |
| Table 3.3-12 Choice(s) in Starting Point XIII | 80 |
| Table 3.3-13 Choice(s) in Starting Point XIV | 81 |
| Table 3.3-14 Cognitive rules and related actions of the three local architectural cues..... | 82 |
| Table 3.3-15 Choice(s) in the fourteen Starting Points | 83 |
| Table 3.5-1 Value ranges of the five attributes..... | 96 |
| Table 3.5-2 Number of the levels and the scenes for every cue pair type | 96 |
| Table 3.5-3 Encoding plan of the Scene D-D for experiment design and data analysis..... | 97 |
| Table 3.5-4 Encoding plan of the Scene E-E for experiment design and data analysis..... | 98 |
| Table 3.5-5 Encoding plan of the Scene S-S for experiment design and data analysis | 99 |
| Table 3.5-6 Encoding plan of the Scene S-E for experiment design | 100 |
| Table 3.5-7 Profile of Scene No.39 in Stair-Exit set..... | 101 |
| Table 3.5-8 Mapped values of Scene No.39 in Stair-Exit set | 101 |
| Table 3.5-9 Depiction of the two cues of Scene No.39 in Stair-Exit set..... | 101 |
| Table 3.5-10 Encoding plan of the Scene S-E for data analysis | 104 |
| Table 3.5-11 Recorded choice of Scene No.39 in Stair-Exit set..... | 104 |
| Table 3.5-12 Performance of the function | 106 |
| Table 3.5-13 Influence ability of the cue attributes | 109 |
| Table 3.5-14 Overview of the Ratio-Probability curves | 110 |
| Table 3.5-15 Estimated B values..... | 115 |
| Table 3.6-1 Bin definition of A1 for all the three cue types..... | 117 |
| Table 3.6-2 Bin definition of A2 for Doorway Entrance and Exit..... | 117 |
| Table 3.6-3 Bin definition of A2 for Up Stair | 117 |
| Table 3.6-4 Decision process with the cues in every step..... | 119 |
| Table 3.6-5 Attributes of the cues in the cue pool..... | 123 |
| Table 3.6-6 Paired comparisons | 123 |
| Table 3.6-7 LEEI report of the multi starting points on B2 level | 126 |
| Table 4.2-1 Encoding plan for distance attribute | 133 |
| Table 4.2-2 Overview of the comparison between SpaceSensor and the local nearest-exit model | 134 |
| Table 4.3-1 Overview of the comparison between SpaceSensor and Simulex..... | 136 |

1 Introduction

In this chapter, first the motivation of the research is introduced, which leads to the three research questions. Next, the research method is briefly explained, which features the CAVE-based virtual evacuation experiment. Furthermore, the contributions of the research are suggested from the view of the architecture profession. Finally, the organization of the contents in the chapters is presented.

1.1 Motivation

The general motivation of the research behind this thesis is to build an architect-oriented computational model to support the evacuation evaluation on complex public underground space design. As a demand from real-world projects of complex public underground development, the question on evacuation evaluation is also put in front of architects. One of their ways to improve the evacuation evaluation is to get more understanding on the architectural cue offered by their space design to evacuees.

1.1.1 Demand from Real-World Projects

The development of complex public underground projects is inevitable in mega cities. With endless land demand, mega cities have to develop their underground network through hundreds of projects for decades. In almost every project, to achieve convenient transportation and high commercial value, development probably includes a multi-story subway station and the full connections to various underground spaces of surrounding commercial buildings with multi functions, which make such a project always containing a complex public underground environment.

All the parties in the development are always very cautious about the evacuation performance of these projects. Several circumstances can make the evacuation in complex public underground environment much harder than in normal buildings. The most deathful one is that smoke always goes up to the same direction as evacuees move. The evacuees will suffer more and more from the smoke during the movement. Moreover, people feel more difficult to find their way, or the evacuation route in emergency, in underground environments (Arthur & Passini, 1992; Carmody & Sterling, 1983). With more complexity of such environments, the difficulty to evacuate can only increase. Furthermore, the failure to find the way out will increase the stress, which makes the evacuation even more difficult.

As one of these parties, architects are also seeking the way to evaluate their designs to reveal the potential evacuation problems, from which they can improve the evacuation performance of these projects. Following this idea, the research behind this thesis starts.

1.1.2 Architectural Way to Improve Evacuation Evaluation

Nowadays, the performance-based approach is regarded as a better choice to evaluate the evacuation design of complex buildings. The traditional prescriptive regulation is used to deal with the regular buildings with simple forms. The plans are divided into zones with assigned exits. It is assumed that the evacuees will always find their shortest way out to the assigned exit of the zone (Shih, Lin, & Yang, 2000). To some extent it works well in the plans with simple forms. However, the evacuees do not behave as assumed in the space with a complex layout. As a solution to deal with the complex layout, the performance-based approach is developed, which relies on the computer-based evacuation models (Bryan, 2002). Such models can predict Available Safe Egress Time (ASET) and Required Safe Egress Time (RSET). Only if ASET is longer than RSET, the design is regarded safe (Tubbs & Meancham, 2007).

Consequently, the prediction of ASET and RSET is the crucial part of the performance-based evaluation approach. ASET is the time period that the physical environment can hold people safely against the fire and smoke etc. since the evacuation alarm. ASET is calculated according to the

structure and the material of the design through the Computer Fluid Dynamics (CFD) formulas. RSET is the time period that people move to safety since the evacuation alarm, which is calculated according to the human behavior knowledge. Obviously, diverse human being as the object of the human behavior knowledge makes the prediction of RSET much more difficult than the prediction of ASET.

Obviously, to predict how the evacuees search the route to the safety is the foundation of RSET calculation. A wrong predicted route would probably result in a wrong RSET, which is calculated according to a wrong egress distance and a set of wrong events during the evacuation. If RSET is underestimated in such a case, the risk will be very high.

As argued by way-finding researchers, evacuee's route will be influenced by all the information about the potential safety derived during the searching process. Such information is so-called *cues*, which can be perceived and used as an impetus for the decision making in the route searching behavior. For example, the threatening cue about where fire locates will enable evacuees to adjust route to avoid it; the cue of the other evacuees' movement will encourage the evacuees to follow; the graphic cue of the signage will provide the evacuees an efficient egress direction, and so on.

Therefore, the improvement on evacuation evaluation can be expected from a better understanding of how the various cues influence the evacuees to search the route. The evacuation evaluation on the space design of the complex public underground environment holds the same expectation. With more knowledge of how the cue works, the designers can generate a better alternative design initially. Additionally, more reliable computer evacuation model can be built to support the evaluation process. Thus, the investigation on all kinds of cues from various professions is needed.

In architectural profession, one of the most basic cues that architects should understand is the architectural cue from their space design. Any design starts from the architect's space design. Collaborating with other designers, the architect integrates more and more details into the space design in the following design process, such as the structural configuration, the electronic equipment, the ventilation system, the water system, even the signage system designed by the graphic designer in the final stage. Such a process keeps the architect's work, the initial space design, a very fundamental position for the evacuation design. A badly designed initial space will offer the misleading architectural cues to the evacuees and leave lots of problems to solve for the other designers, such as the signage designers. Meanwhile, the patchwork sometimes causes further confusion rather than clear guidance. And it is not easy to change the space configuration with almost all the details decided in the final design stage. Thus, architects should understand which cue is offered by their space design and how the cue influences evacuee's behavior, which is the way to improve the evacuation evaluation for them.

In summary, taking the performance-based approach as a proper way of the evacuation evaluation for complex buildings, architects are expected to understand more about the architectural cues from their space design to improve their evacuation evaluation in these complex projects. Obviously, the project of complex public underground environment holds the same expectation.

1.1.3 Architectural Cue in Evacuee's Route Searching

It is not a new topic for architects to explore how the architectural cues from their space designs influence evacuees' route searching. The way-finding researcher Passini (1984) raises a consideration on the architectural information by arguing, "Although the architecture and the spatial

Architectural Cue Model in Evacuation Simulation for Underground Space Design

configuration of a building generate the way-finding problems people have to solve, they are also a way-finding support system in that they contain the information necessary to solve the problem.” Actually, he reminded two basic directions for the exploration, namely the local architectural cue named as “architecture” and the global architectural cue named as “spatial configuration”. These two kinds of cues form all the contents of the architectural cue from space design and they act as the only input of the evacuation evaluation on the space design.

The global architectural cue is the information about how the parts of the environment are organized together. Lynch’s (1960) mental image of the city can’t be ignored here as a root of this kind of research, although it offers an approach to describe how the parts of the environment are organized at an urban scale. Kuipers’ TOUR model (1978) might be the first computational model for the global architectural cue. A more successful model is Hillier’s space syntax (1996), which offers not only a representation of the space organization but also a computational model, which the designers can use to calculate indexes to understand the organization quantitatively. More details about such models are introduced in Section 2.1.3.

The local architectural cue is the information that hints the immediate egress direction based on the features of the visible local architectural elements, such as doorway entrances, stairs, exits etc. The root of this kind of research is Gibson’s concept of affordance (1966), in which it is argued that every perceived object in the environment has a related affordance that hints its usage to the observer. For example, a doorway entrance affords the possibility to pass through; a stair affords the possibility to go to another floor; an exit door affords the possibility to leave the building to the outdoor. Furthermore, these affordances have different level of attractiveness, which influences their usage. Some evacuation simulation models use a sub model to handle the local architectural cues according to this concept in a very subjective way, such as BGRAF (Ozel, 1987), which assigns a set of user input values called architectural preference levels to the local architectural elements. The simulated evacuees will be attracted by these elements in different extents. Also, more details about this kind of cue are introduced in Section 2.1.3.

In evacuation evaluation on the space design of complex public underground environment, the global architectural cue is excluded from the simulation model behind evaluation with some conservative reasons and assumptions. Although the global architectural cue has been configured in the space design, it is hardly perceivable during the evacuation in complex public underground environment. The global architectural cue can be perceived during previous or current visit (Golledge, 1999a). In either kind of visit, it can be perceived from the architectural forms, such as the circulation system (Arthur & Passini, 1992), the exterior form of the building (Arthur & Passini, 1990), the visible structural frameworks (Werner & Schindler, 2004), and the atrium (Passini, 1984). However, it may take risks to assume that the visitors in a public space have any previous visiting experiences. Moreover, it is very difficult for the evacuees to understand the whole space according to a part of its circulation systems, which might be designed in a totally different logic by different architect. Furthermore, the underground environment hasn’t any exterior form to understand. It also rarely has an atrium or a regular structural framework according to structural and economic reasons. Consequently, the global architectural cue is not perceivable as reliably as it is in normal buildings. The only cue from the space design still perceivable is the local architectural cue. Thus, architects should put more energy to investigate how the local architectural cue works quantitatively.

Unfortunately, the architects’ understanding on the local architectural cue is still not enough to support a proper computational model, which can predict how the space design influences the evacuees to search the route to the safety. It is the evacuation expert with the specific knowledge of the model parameter who is the only person to manipulate the existing evacuation models to do the

performance-based evaluation for architects in the final design stage (Papamichael, LaPorta, & Chauvet, 1997; Shih, Lin, & Yang, 2000). Although there is still a debate on whether the simulation tool should be used by the experts or the designers (Augenbroe, 2001), it must be beneficial if the architect can have a clearer understanding on his own design object and be able to do the evaluation by himself in all the design stages, especially in the initial stage of space design (Hensen, 2004; Hopfe & Hensen, 2006; Hopfe, Hensen, & Plokker, 2007; Struck, Kotek, & Hensen, 2007).

In summary, architects have to quantitatively investigate how the local architectural cue influences the evacuees' route searching behavior in the evacuation evaluation on the space design of complex public underground environment. With such knowledge, architects can be sure that their initial space design works just as they planned, which provides a better starting point for the following design process. At the same time, the correspondent computational model can predict what route the evacuees will take driven by the space design, which can be compared with the other planned routes, such as the route driven by the signage system, to ensure all the cues work coherently. Thus, a computational architectural cue model is aimed in this research.

1.1.4 Research Field and Questions

With the above motivation, my research will focus on the following three questions crossing over several research fields (Fig.1.1-1).

- 1) How does the space design of complex public underground environment influence evacuee's route searching process?
- 2) How can such a process based on local architectural cue choice be modeled in an architect-oriented evaluation tool?
- 3) How can such a model be validated?

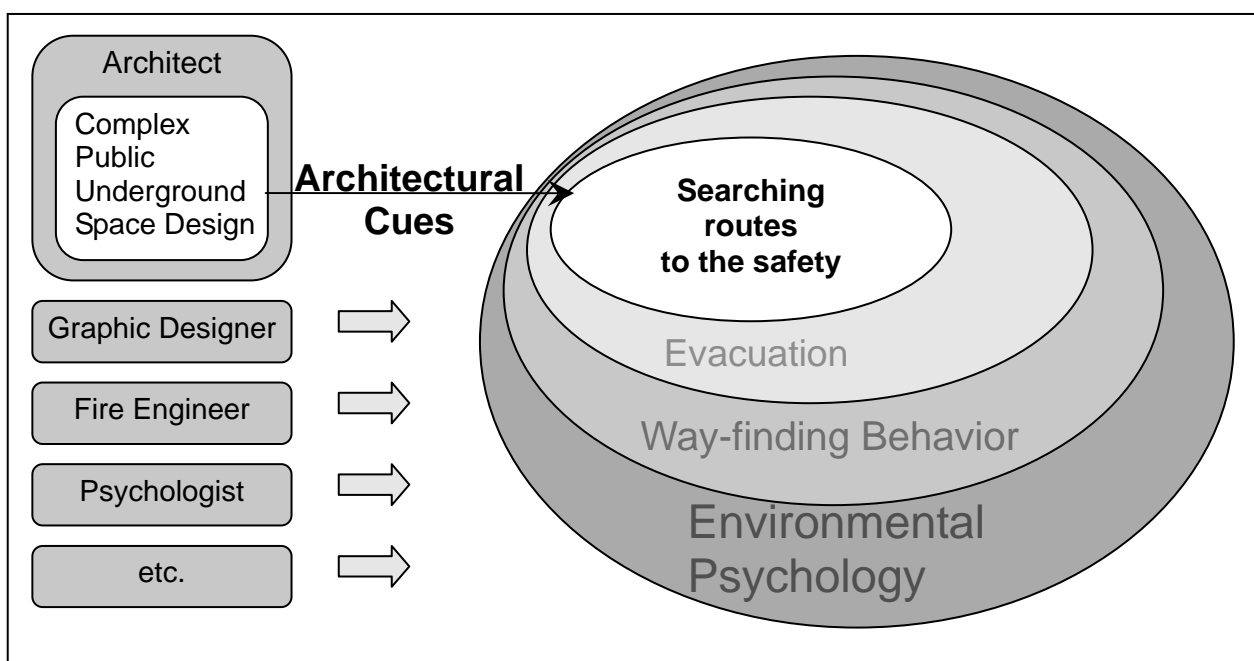


Figure 1.1-1 Research fields

As other researchers investigating their objects from the views of their own professions, in this research, the view of architectural space design is leading, or even more specific, the complex public underground space designs. From it, the evacuee's behavior is studied, searching routes to

the safety, through the medium called the architectural cues. During the research, several related research fields are crossed from specific to general, they are: evacuation behavior, way-finding behavior, and environmental psychology.

1.2 Method

Six steps (Fig.1.2-1) are planned and implemented to answer the research questions. The first step relates to the first research question. The steps from the second to the fifth relates to the next research question. The last step relates to the final research question.

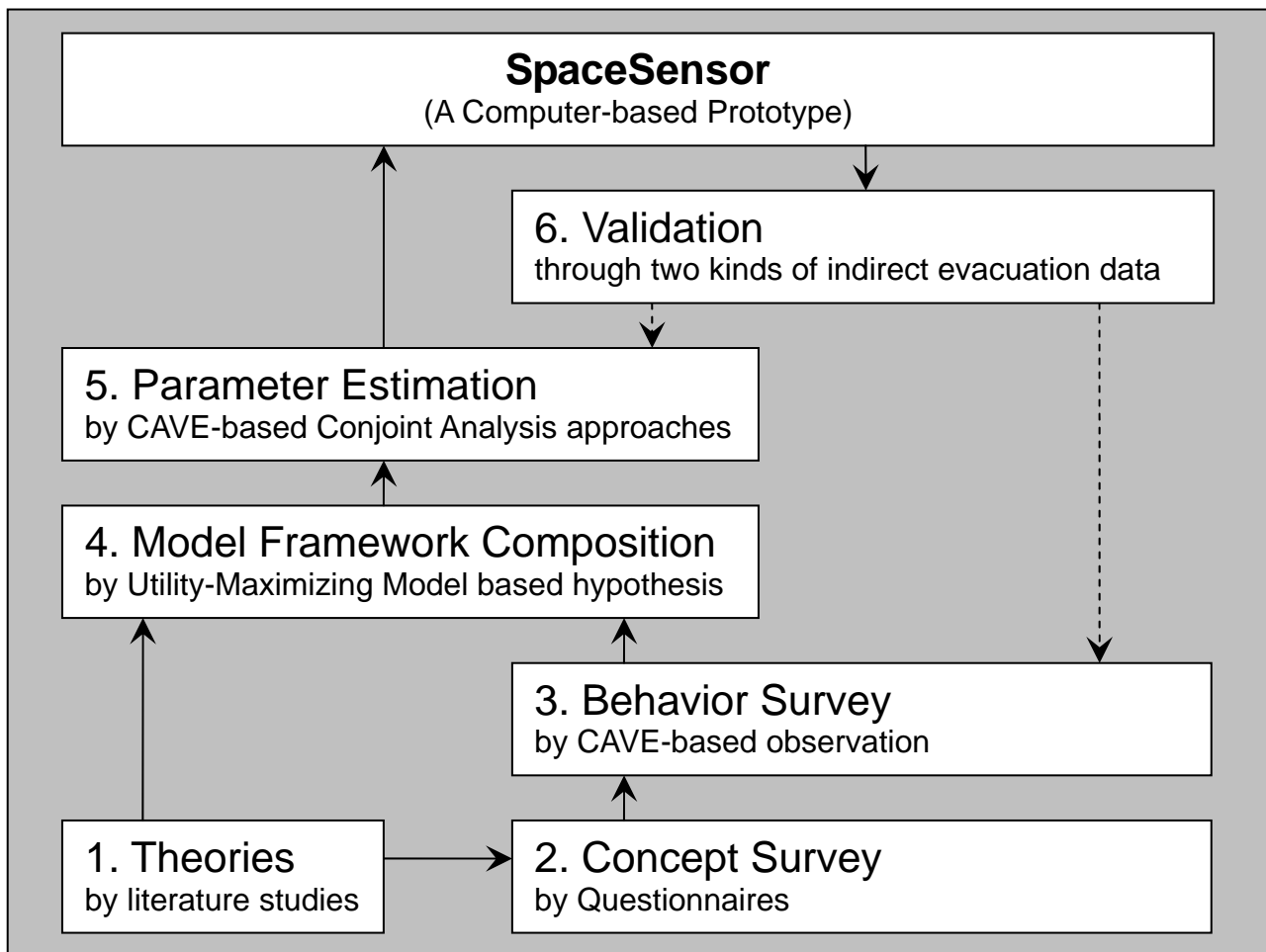


Figure 1.2-1 Research methods

The first step is the literature study focused on the related theories of the evacuees' cue-based route searching behavior. The theories about cues in evacuation are studied in a way-finding context. Several topics, such as the perception process of cues, the diversity of cues, the decision process upon cues, and the interaction of different cues, are discussed. Then the specific context of the complex public underground space design is studied to confine the research object. Next, 36 evacuation models are analyzed in the context of architectural cue modeling. With the conclusion that these models haven't made a good use of the local architectural cue and share some limitations, the challenge of the research is raised. Finally the potential research method is suggested for the following investigation.

After this step, the first research question is answered. Moreover, five further questions are raised during this literature study. Following these questions, this research is planned with the remaining steps.

The second step is to create an overview of the local architectural cues used in the research context by questionnaires. A ranking list of the available local architectural cues in the research context is compiled from more than one hundred samples. According to the building codes in design practice, three basic types of local architectural cues are selected as the elements of the following research.

The third step is to build a special platform to observe the evacuees' responses to the three selected cues. The local architectural cue is a kind of abstract object, which can't be investigated independently in the real environment with the interference from the other kinds of cues. However, the virtual reality technology provides the possibility to create the local architectural cues with the other cues controlled and to visualize all kinds of customized scenes conveniently. Thus, a special CAVE system is built up to provide the participants the virtual scene in the space design of complex public underground environment. With the records of more than one hundred participants' virtual evacuation, the platform is proved reliable in the observation of evacuation traces. From this, some preliminary choice preferences related to the elementary cues are concluded.

The fourth step is to hypothesize a computational model framework explaining how the evacuee uses the three selected cues to search his route to the safety according to the literature studies and the conclusions of the above two steps. A simple cue-based loop consisting of perceiving phase, choosing phase and approaching phase is composed. The components of each phase are designed. The perceiving phase uses an artificial vision recognition algorithm, which enables the simulated evacuee to perceive the three selected cues. The choosing phase uses a preference prediction function, which enables the simulated evacuee to choose a cue among the perceived ones as the goal of next movement. The approaching phase uses the shortest path planning algorithm, which enables the simulated evacuee to get closer to the chosen cue while avoiding obstacles.

The fifth step is to estimate the parameters of the preference prediction function through the virtual evacuation experiment. The Conjoint Analysis approach is applied here with the support from the customization and interaction capabilities of the virtual reality technology (Dijkstra & Timmermans, 1997). With the seven attributes of the three selected cues defined, sets of virtual scenes with paired cues are generated according to the fractional factorial design technique. Hundreds of participants make the choice between the paired cues in every scene during the experiment. With these choice data, the parameters are estimated by the Multinomial Logistic Regression.

After this step, a computer-based prototype is built to demonstrate the proposed model, with which the second research question is answered.

The sixth step is to validate the proposed model. After a discussion on the virtual-reality-based validation method, two sets of indirect evacuation data collected in the previous experiments are used as references to examine the proposed model. In the first set, the prediction abilities of the proposed model and a model using the *local* nearest-exit assumption are compared with each other referring to the participants' static cue choices observed in the previous experiment. In the second set, the prediction abilities of the proposed model and a model using the *global* nearest-exit assumption are compared with each other referring to the participants' dynamic cue choices observed in the another previous experiment.

In a summary, the composition of the model framework is based on the literature study, the

questionnaire survey, and the observation experiment. The parameters of this model are derived in the estimation experiment supported by the CAVE-based Conjoint Analysis approach. The validation is conducted with two sets of indirect evacuation data collected in virtual-reality-based experiments.

1.3 Contributions

The main contribution of this research is to provide a quantitative understanding on how the architectural cues influence the evacuees' route searching behavior in a space design of complex public underground environment. It is the foundation of both knowledge about space design and performance-based evaluation for space design.

A quantitative understanding provides the possibility that architects can ensure that evacuees will make use of the architectural cues in the way as they planned. The existing knowledge about the evacuation is hypothesized by the architect according to his personal experiences and predictions. The prevalent phenomenon that architects always have different opinion from the users on their buildings indicates the obvious gap between the architects' prediction and the real human behavior (Rapoport, 1982; Deasy & Lasswell, 1985; Lawson, 2001; Carpman & Grant, 2002). As argued previously, such a gap must lead to an initial space design with misleading architectural cues, which is a big risk to the whole evacuation design. Therefore, such a quantitative understanding can enable the architect to predict the evacuees' response much more closely to the real users' responses. Actually, it improves the space design in the evacuation aspect, as well as the whole evacuation design.

Moreover, a quantitative understanding is the natural foundation of a computer-based model for performance-based evacuation evaluation. Such an evaluation tool for complex public underground space designs can be used both in the initial design stage by architect himself to ensure the proper manipulation of the architectural cues and in the following design stages to ensure the coherence between the architectural cues and the other kind of cues.

In summary, the research result is a computational model demonstrated by a computer-based prototype called SpaceSensor, which can explain and simulate the process of the evacuee searching the route to the safety according to the architectural cues in the space design of complex public underground environment. As an architect-oriented evaluation tool, this model and the corresponding prototype can assist the architect to improve the evacuation performance of his complex public underground space design.

1.4 Dissertation Overview

Chapter 1 is an introduction of the research. More light is put on the motivation.

Chapter 2 relates to the 1st step of the research method and answers the first research question. First, it introduces the background theories related to the evacuees' cue-based route searching in the context of way-finding. Next, it introduces the strategies of the existing evacuation models on how to use the architectural cues to drive the evacuees' route searching, in which the limitations of these strategies are also analyzed. Last, it suggests the potential solution to improve the strategy.

Chapter 3 relates to the 2nd-5th steps of the research method and answers the second research

question. First, it sets the detailed aims for the modeling work. Next, it introduces how to use the questionnaires to get a general understanding on the local architectural cues, how to build the CAVE-based platform to observe the evacuation behavior, how to hypothesize a computational model framework, and how to use a CAVE-based Conjoint Analysis approach to estimate the parameters of the model one by one according to the steps of the research method. Last, it introduces a computer-based prototype SpaceSensor demonstrating “How can such a process based on local architectural cue choice be modeled in an architect-oriented evaluation tool?”

Chapter 4 relates to the 6th step of the research method and answers the last research question. It introduces how the two sets of indirect evacuation data are used to prove the validity of the model and to indicate its improvement from the existing models.

Chapter 5 is the conclusion of the research. First, the whole research is summarized with the motivation, the research process, and the contributions. Next, based on the research result, three guidelines are suggested for the space design of complex public underground environment from an architect’s view. Finally, the thesis is ended with the future direction of this research.

2 Reviews on Cue-based Evacuation Researches

As argued in Chapter 1, the prediction of the evacuees' routes is crucial for performance-based evaluation. This chapter introduces the related researches on how the evacuees' search their route to the safety from an architectural view within the way-finding context. It answers the first research question, "How does the space design of complex public underground environment influence evacuee's route searching process?" Additionally, the strategies of the existing evacuation models on how to use the space design to influence the evacuees' route searching are discussed. The limitations are concluded and the investigation method is suggested.

2.1 Cue-based Evacuation

First the way-finding theories are introduced as the literature context, in which the process of the evacuee searching the route to the safety is explained as a way-finding process. Afterwards, several related topics are discussed. They are the perception of cues, the diversity of cues, the decision making with cues, and the interaction between cues.

2.1.1 Evacuation as a Type of Way-finding

Although there are many notions covering the aspects of evacuation, such as the notion of Fire Response Performance, which gives a very complete list on these aspects (Kobes et al, 2008), way-finding is always a central aspect concerning the human behavior and it is the closest one to the context of evacuee's route searching in this thesis. Argued by the way-finding researcher Arthur and Passini (1992), the evacuation behavior, namely searching the route to the safety, is a type of way-finding process in emergency, which shares the way-finding research field with the other two types: Normal way-finding and Recreational way-finding. Thus, the research here will start with the way-finding theories as a literature context for all the following discussion.

1) Definition of Way-finding

During the investigation on the "legibility" of the cityscape, the American architect Kevin Lynch invented this term "Way-Finding" in his book *The Image of the City* (1960). Afterwards, several definitions were given by the researchers from the different views.

From the view of perceptual activity, it was defined as the purposeful movement to a specific destination that is distal and, thus, cannot be perceived directly by the traveler (Allen, 1999). Furthermore, it is explored as the associated cognitive and perceptual processes in detail (Golledge, 1999b).

From the view of the guiding process of the human movement, it was defined as "The process involves selecting paths from a network, and is called path finding or way-finding. For successful travel, it is necessary to be able to identify origin and destination, to determine turn angles, to identify segment lengths and directions of movement, to recognize on route and distant landmarks, and to embed the route to be taken in some larger reference frame. This information is required to plot a course designed to reach a destination (previously known or unknown) or to return to a home base after wandering" (qtd. in Golledge, 1999a). Similarly, way-finding was defined as one component of navigation for route planning, which works with the other component called locomotion (Montello, 2005; Montello & Sas, 2006).

From the view of mental activity, it was defined as "'Way-finding' was the term introduced to describe the process of reaching a destination, whether in a familiar or unfamiliar environment. Way-finding is best defined as spatial problem solving." (qtd. in Arthur & Passini, 1992). Similarly, it is defined as a hierarchical series of decisions making when people are looking for their way (Passini, 1984).

From a systematic view, the term was defined as a system, a combination of behavior, operations, and designs by Weisman (Carpman & Grant, 2002). Such a definition covers almost every aspect of

the way-finding researches concerned by the other researchers, and the definition integrates these aspects into a coherent system, which provides a complete understanding on this term.

Thus, Weisman's way-finding system is regarded as a theoretical framework with complementary components from other researches appended to it for this research. This system is explained in detail in the following paragraphs.

2) Framework of the Way-finding System

Weisman (Carpman & Grant, 2002) argues that it is necessary to regard way-finding as a multi-dimensional, interconnected system including three basic components: the human behavior, the environmental design, the organizational policies and practices. From this view, the research of way-finding is broadened from the psychologists' interest to an integrated field with the additional two other professions: the environment designers and the facility managers. Consequently, as a system, the way-finding performance depends not only on the performances of every component but also on the coherence between them. The three components are introduced briefly in the following to provide an overview beyond the professional boundaries.

First of all, the traditional aspect of the way-finding, Behavior Element, is presented. This component tries to explain the human beings' strategies in way-finding. The following four strategies are concluded by Weisman.

“The first strategy involves seeing one's destination and moving steadily toward it.” (qtd. in Carpman & Grant, 2002) This strategy is the basic principle of human movement.

“The second way-finding strategy involves following a path that leads to a destination.” (qtd. in Carpman & Grant, 2002) The path can be the continuous cueing devices, such as colored floor lines, used in hospitals. It is very useful to drive the way-finding in a complex environment but with a relative few number of starting points and a destination. Otherwise, the sensory overload will happen, which is mentioned by Weisman.

“The third strategy uses environmental elements, like signs and landmarks, to provide information along the way.” (qtd. in Carpman & Grant, 2002) This strategy is especially useful when the human being is not familiar with the environment. The environmental elements so-called “cues” are used for a dynamic decision making along the route. Usually the human being doesn't have a planned route before he starts. He makes sequential decisions to search the route. Actually the first and the second way-finding strategies are two subsets of this strategy, if the visible destination and the color information continuously forming the path are both regarded as two kinds of environmental elements along the way.

“The fourth strategy involves forming and using a mental image or cognitive map of the environment at hand.” (qtd. in Carpman & Grant, 2002) This strategy is prevalently used when the human being is getting familiar with the environment. Then he can plan a route to follow before he starts.

All the four strategies are not used independently. Actually they work together and influence each other according to the different environment conditions, the familiarity with the environment, and the available cues in the environment.

Architectural Cue Model in Evacuation Simulation for Underground Space Design

The second component is called Design Element. The cues offered by the environment are a big part of the input to the decision making for all the strategies. Consequently, the design of these cues will have a great influence on the human beings' way-finding behavior. Mentioned by Weisman, "Facility layout, Architectural and interior design differentiation, Landmarks, Signs, Maps, Lighting" (qtd. in Carpman & Grant, 2002) are the six design elements, which designers should manipulate carefully for the human being's way-finding. However, the design element is not restricted to the above. A more complete category is introduced in the Section 2.1.3.

The third component is called Operational Element, which includes the issues of Terminology, Way-finding staff training, Pre-visit information, and Way-finding system maintenance. This element is more like the glue between the other two elements. It contributes to the way-finding by "soft" means. The sign can be much clearer with the improvement of terminology. The extra cue of oral information could be provided through way-finding staff training. The familiarity with the environment could be increased through providing more pre-visit information. Every cue can work coherently and sustainably with the way-finding system maintenance.

In summary, Weisman's explanation broadens the view of way-finding. However, as mentioned above the first and second strategies can be combined into the third strategy. Three of them share the feature that the individual uses the information perceived along the way to search the route to the destination without a pre-decided plan, which is a radical difference from the fourth strategy to plan and follow a route. Thus, it is suggested to redefine the way-finding strategy into two items:

1. To use all kinds of information from the environmental elements along the trip to search a way without a plan. Several more detailed strategies can be found falling into this category, such as the least-angle strategy (Hochmair & Frank, 2000; Hochmair & Luttich, 2006) and the direction strategy (Holscher, Bolhner, Meilinger, & Strubea, 2008; Holscher, Meilinger, Vrachliotis, Brosamle, & Knauff, 2006).

2. To use pre-stored knowledge about the environment in the brain to follow a route with a plan. Several more detailed strategies can be found falling into this category, such as the fine-to-coarse strategy, the floor strategy, and the central-point strategy (Holscher, Bolhner, Meilinger, & Strubea, 2008; Holscher, Meilinger, Vrachliotis, Brosamle, & Knauff, 2006).

3) Process of Way-finding

Although Weisman's way-finding system explains which static elements are in this behavior system, the dynamic process is not touched. Complementarily, Arthur and Passini's theory of way-finding process (1992) is discussed in the context of the above system. They describe the way-finding process as problem solving, which includes the following steps:

The first step is to "take into account the previous experiences" (qtd. in Arthur & Passini, 1992). Such "previous experiences" are the same notions as "the mental image and cognitive map" described in the second redefined Weisman's strategy.

The second step is to "rate and evaluate the environmental context" (qtd. in Arthur & Passini, 1992). Just as mentioned in the strategy summary, the usage of a specific strategy relates to the environment conditions, the individual familiarity with the environment, and the available cues. Thus, these conditions have to be rated and evaluated, before the individual implements any strategy subconsciously.

The third step, “try to understand the spatial characteristics of the setting” (qtd. in Arthur & Passini, 1992), and the fourth step, “take in the information displayed on signs, maps, and indicators”, both relate to the first redefined Weisman’s strategy, in which the individual searches all kinds of cues to find his way. One thing worth discussing is that Arthur didn’t make it clear what “the spatial characteristics of the setting” is in his writing. In the architecture profession, it can be explained as either the characteristics about the global organization of all the parts in the environment or the characteristics of the local architectural elements in the vision, or perhaps the both. For example, the circulation system in the former explanation can help the individual to understand the characteristics of the global environment even though he hasn’t visited all the parts of the environment. Like local architectural elements doorway entrances and stairs can also help the individual to understand the characteristics of the local environment, such as where to go ahead and where to go up or down into another level.

The fifth step is to “assess different options” (qtd. in Arthur & Passini, 1992). If the mental image, the cognitive map, and the previous experiences are explained as a pre-stored cue in the individual’s brain about the global environment characteristics, the “different options” are actually a set of cues, which offer information partially or fully, correctly or wrongly about how to find the way. In this step, both the two redefined strategies are represented as the means to use the specific types of cues. These cues are classified according to their hint on the moving direction. Then the reliability of the hints is assessed in this step.

The sixth step is to “consider the time factor, the interest, or the security that goes with taking a given route” (qtd. in Arthur & Passini, 1992). In this step, the individual has to choose a direction to go ahead within the constraints of the time factor, the interest or the security etc. The reasoning process is tightly related to the above assessing step. More details will be introduced in the field of the human decision theories in Section 2.1.5.

Meanwhile, Raubal and Egenhofer (1998) raise a similar but simpler version of the way-finding process, called “Choice-Clue model”, in which the choices are done at the decision points during the way-finding process when the individual is facing more than one direction to go ahead. The clues are the information from the environment elements, such as signs and architectural features, relating to Noman’s (1988) concept of “Knowledge in the world”. The whole process is explained as a loop of perceiving the clues and choosing the clues to go ahead. Inheriting such a model, Xia et al (2008) develops a set of models for different way-finding situations. However, they all share a similar loop structure containing the individual’s cue perception and decision making.

In summary, Arthur’s steps from one to four are focused on the perception of the various cues from the environment, and the steps five and six are focused on the choice in the cue-based decision making. Such a process has a strong relation to Raubal and Xia’s two-step loop model. It is suggested to redefine their models as “Cue-Choice Model”. In every step, there are three phases:

1. The individual searches all the cues including both the previously perceived cues in his brain and the real-time perceived cues from the environment.
2. He chooses one cue with its hinted direction as the goal of the next step according to the situation and his knowledge.
3. He moves to the goal.

4) Researches of Way-finding

Since the concept of way-finding was raised by Lynch in 1960, there have been many researches in this field. As revealed by the integrated view from the way-finding system, these researches can be classified according to the researchers' background. They are psychologists, designers, or built environment managers, sometimes even a mixed team. These researches can also be classified according to Gluck's result-based classification: performance-oriented and competence-oriented way-finding researches (Raubal & Worboys, 1999), which gives us the clearer view on how these researches can support a computational way-finding model in this research context.

a. Performance-oriented Way-finding Researches

This kind of research tries to find what can influence the individual way-finding performance, in other words to define the causal variable. Lynch (1960) uses the sketches and interviews to discover the inhabitants' mental image of the city, which consists of five basic elements: nodes, paths, landmarks, edges, and districts. He concluded the legibility of the city, in other words the way-finding performance in the city, correlates to the quality of the mental image provided by the city. Weisman (1981) puts his focus on other environmental variables that influence the way-finding performance and concludes four such factors: the visual access, the architectural differentiation, the signs and room numbers to provide identification or directional information, and the plan configuration. These variables are also supported by the other researchers (Garling, Book, & Lindberg, 1986; Raubal & Worboys, 1999; O'Neill, 1991a; O'Neill, 1991b; Seidel, 1982; Dogu & Erkip, 2000). Besides, Garling, Lindberg, and Mantyla (Raubal & Worboys, 1999) and Seidel (1982) discover another important variable, the individual's familiarity with the environment.

b. Competence-oriented Way-finding Researches

This kind of research tries to build a model to explain how the individual finds his way out with all the above variables. Kuipers' TOUR model is regarded as the starting point of this field (1978). He transforms Lynch's five formal elements into five computational notions, based on which the model is built to simulate the process that an individual uses the mental image to find his way. From then on, several models simulating the cognitive process are developed, such as McCalla's ELMER, McDermott's SPAM, Leiser's TRAVELLER, Gopal's NAVIGATOR, Epstein's ARIADNE, and Raubal's Choices-Clue Model (Raubal & Worboys, 1999).

In summary, the performance-oriented researches can be regarded as the foundation of the competence-oriented researches. The former explains what will influence the way-finding process by a set of variable definitions; while, the latter tries to explain how the process works with these variables. One barrier of the latter research is from such a transition, in which the qualitative variable definitions have to be mapped into a quantitative model driving the behaviors. Another notable barrier is that the competence-oriented research needs more understanding of the individual commonsense knowledge about the environment, in other words how the individual cognizes and uses the environment element, which can support the way-finding computation in a higher level. However, it still demands more investigation as mentioned by Golledge (Raubal & Egenhofer, 1998).

5) Evacuation Behavior

The above sections are the brief introductions of the way-finding theories, which are regarded as the background of the evacuation behavior theories. As mentioned before, the evacuation behavior is one of the three way-finding modes. Ozel (1987) argues, “Way-finding is obviously central to any discussion related to emergency egress behavior.” The evacuation behavior can be defined as a special way-finding behavior taking any safe place as the destination (Arthur & Passini, 1992). Meanwhile, the evacuation behavior theories inherit all the results and barriers from the way-finding theories.

a. Framework

With the same systematic view, evacuation behavior is influenced by the same three elements as way-finding behavior: Behavior Element, Design Element, and Manage Element (Carpman & Grant, 2002).

Within Behavior Element, the individual inherits two redefined strategies: One is to use all the perceived cues to search the route to the safety without a plan or known destination. The other is to use the mental image, which is formed by either the cues perceived previously or the cues perceived currently, to plan and follow a route to the safety or a known destination. Notably, in the evacuation context, an additional strategy is mentioned in the literatures that the evacuees would like to leave the building through the same route as they enter (Johnson & Feinberg, 1997). Furthermore, at a higher decision level, four general egress strategies are defined by Tubbs and Meancham (2007) as: protect in place, relocation to a safe place, phases evacuation, and simultaneous evacuation. However, in this research context, the investigation on how the evacuees search the route to the safety, the first three general strategies are not considered for the strong guidance put on the evacuees. Only the Simultaneous evacuation is considered.

Within Design Element, the cues from all the environment elements can influence the evacuee’s decision.

Within Manage Element, the clarity of the terminology, the evacuation staff training, the evacuation plan, and the evacuation system maintenance can all influence the evacuees.

b. Process

Concerning the precious time during the evacuation behavior, its process is analyzed into more detailed phases by the researchers. Two main phases are recognized in the evacuation process. They are the pre-movement phase and the movement phase. The former starts when the first alarm of any disaster is perceived and lasts until the people begin to move. The latter starts with the people’s movement and lasts until people arrive at a safety or die (British Standards Institution, 1997; Graat, Midden, & Bockholts, 1999). The second phase is divided into three sub phases according to security level of the space, where the evacuees locate. They are evacuation behaviors in Occupied Rooms, Exit Accesses, and Exits. The Occupied Rooms are the spaces holding most of the people in normal situation. The Exit Accesses are the spaces through which occupants must traverse to reach an exit, and include rooms, aisles, doors, corridors, stepped aisles, open stairs, unenclosed ramps, and similar elements that enable the occupant to get from an Occupied Room to the safe part of the building. The Exits are the spaces regarded as the safety, which separated from other interior spaces

Architectural Cue Model in Evacuation Simulation for Underground Space Design

by fire-resistance-rated construction and opening protective spaces (Tubbs & Meancham, 2007). In this research context, the evacuation behavior within Exit Accesses during the movement phase is focused on. This phase is regarded as a way-finding process. It means that the individual implements this evacuation behavior as explained in the “Cue-Choice Model” (Fig.2.1-1). In every step, there are three phases:

1. The evacuee searches all the cues including both the previously perceived cues and the real-time perceived cues from the environment.
2. He chooses one cue with its hinted egress direction as the goal of next step. The choice criteria relate to the evacuation context and his common knowledge.
3. He moves to the goal.

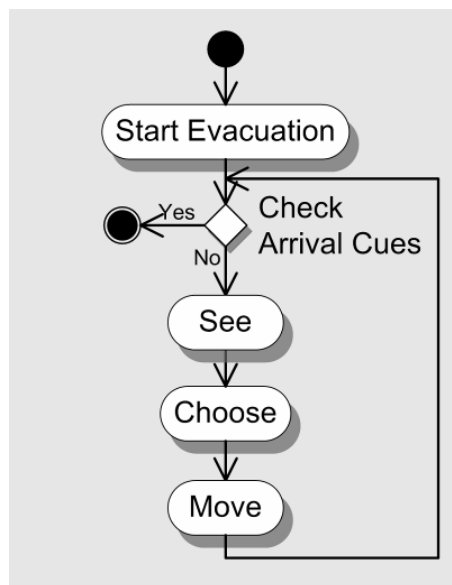


Figure 2.1-1 Evacuation process

c. Researches

Similarly to the way-finding researches, the evacuation behavior researches can also be classified into two categories. The performance-oriented researches try to reveal what variable influences the evacuation performance. The competence-oriented researches try to use these variables to build a model to explain how the individual, or even the crowd, evacuates (more examples in Section 2.3). In such a transition, there is one more barrier in front of the researchers besides the other two inherited from the way-finding researches. Obviously it is extremely difficult to do experiment in a real evacuation concerning the security risks (Sime, 1987; Helbing, Farkas, & Vicsek, 2000). As a result, the researches have to rely on the indirect evacuation data.

d. Stress Effect

One issue making the evacuation behavior special from the other way-finding behavior is the evacuees' stress or even panic. Miller argues that the decision making in emergency might differ from the one in normal situation (Ozel, 1987). To some extent the irrational decision in panic is expected in this research. According to the definition by Fritz and Marks (Hostikka et al., 2007), the panic is caused by two factors. The one is that people assume they are in immediate danger to life.

The other is that they assume that their possibilities to escape the danger are rapidly weakening. However, such an extreme situation is very rare. Many researchers suggested the expectation on human being's panic rarely happens after the intensive observations and experiments. In most cases, the evacuees behave rationally (Sime, 1980; Ozel, 1982; Sime, 1985; Wood, 1990; Bryan, 1996; Galea, 2001). Furthermore, they discover that the stress exists in some extent, and both the positive and negative effects in the decision making process are observed (Gigerenzer, 2000). Fortunately, Arthur and Passini (1992) raise a guideline for the designers to deal with such unpredictable stress, "If a setting works well under normal conditions, it will have a better chance of working well in emergency conditions." With this wise argument, the designers are able to use all the conclusions from the way-finding researches to improve the evacuation design. It means that if an environmental attribute is influential positively in way-finding, it must be influential positively in the evacuation, too.

In summary, the evacuation behavior researches inherit all the theories of way-finding researches. It features that the evacuees will take the safety place as the destination, have an additional strategy to track back the entering route, and make decisions under stress. To build a computational model, three barriers have to be overcome:

- The observation of evacuation behavior by indirect means;
- The transition from the qualitative definition to the quantitative value;
- The knowledge about how evacuees cognize and use the cues.

In the next section, how the cues in the evacuation are perceived will be discussed.

2.1.2 From Perceived Light to Meaningful Cues

Brunswick and Gibson (Canter, 1975) argue the importance of the prevalent available cues on the human being's perception in the environment. Meanwhile, Lynch (1960) also argues, "Human way-finding is based on a consistent use and organization of definite sensory cues from the external environment... Structuring and identifying the environment is a vital ability among all mobile animals. Many kinds of cues are used: the visual sensations of color, shape, motion, or polarization of light, as well as other senses such as smell, sound, touch, kinesthesia, sense of gravity, and perhaps of electric or magnetic fields." The cues with meaning to human beings are the media, through which we can understand the world. As the starting point of the "Cue-Choice" model for the evacuation process, the visual perception of cues is introduced in the following.

1) Visual Perception in Evacuation Context

Although the perception of the cues can be captured by all the human being's senses, the visual perception is undoubtedly the most important and reliable one. The visually perceived cues are focused on in this research context.

The importance of the visual perception is everywhere in the literatures. Leonardo da Vinci (qtd. in Crosby, 1997) argues, "The eye is the master of astronomy. It makes cosmography.... The eye carries men to different parts of the world.... It has created architecture, and perspective, and divine painting.... It has discovered navigation." After hundreds of years, Hall (1966) argues the individual "navigation in every conceivable terrain, avoiding obstacles and danger" relies on the visual perception. Weisman also argues, "The data from environmental cognition literature suggests that visual perceptual access plays an important role in the spatial behavior of people." (qtd. in Ozel, 1987)

Architectural Cue Model in Evacuation Simulation for Underground Space Design

The sovereign position of the visual perception in the way-finding, as well as in the evacuation, doesn't mean other senses are not useful in some situation. It means that they are not always reliable in all the circumstances, which leaves almost all the reliance to the visual perception to avoid any risk. Just as Arthur and Passini (1992) argue, "The value of a sound source for way-finding is often reduced because of the unreliability of the source. Tactual and haptic perceptions apply only to proximal objects. Few would argue that we have lost the ability to follow our noses, although our sense of smell is not usually enough to get us home."

Consequently, any way-finding or evacuation model working at a level of the individual perception should be able to mimic such a visual perception process. Influenced by the human view field and the moving direction, the same environment always offers visual cues differently. Such a difference might lead to the disparity in the route choice, and even in the result of the evacuation. Golledge (1995) did an experiment to compare with the two routes between the same two places but with opposite starting direction. With the result that a route from A to B is so different from the route from B to A, he concludes, "Perceptions of the configuration of the environment itself may influence route choice. Thus, a route that seems shorter or quicker or straighter from one end may not be so perceived from the other end." Similarly, Turner and Penn (2002) introduce their visibility-graph-based pedestrian model with a sharp comment on the other models without visual perception, "What appears to be constraining both Hoogendoorn et al. and Helbing and Molnar is the ability to see. Without it, their models can only be, literally, stabs in the dark at able-sighted human behavior." Although it is unfair to suggest the other models' lack of visual ability if they have the totally different purpose in modeling, the comment itself argues that the visual ability can improve the competence of a model to mimic the individual's movement.

In summary, the visual perception is the main source of the cue-based perception in the context of evacuation. And any modeling work to mimic how the individual uses the cues to search a route to the safety should enable the agent to see the cues in the environment. Before an artificial visual perception process is setup, the human beings' visual perception process is discussed in the following.

2) Visual Perception Process

The research of human beings' visual perception of cues in the built environment starts from the Gibson's Affordance theory (1966), which explains how an object in the environment gets the meaning about the object itself and its potential usage. He interprets the environment as a set of various affordances, which are the units of human being's cognition. The visual affordance is one of the five affordance types for all the human being's senses. With a motivation, the visual stimuli, the light pattern of an object, is cognized as a visual affordance according to the "schemata" of this object in the brain. He explains, "These schemata are partially innate and partially learned, which form the linkage between the [visual] perception and the [object] cognition." Implicitly the potential usage related with this object notion is also cognized with the same schemata in his explanation. As a result, such an affordance is regarded as a cognizable opportunity to use this object for the motivation, and the schemata is regarded as a set of knowledge about this object.

Based on Gibson's theory, Hershberger (1974) develops the mediational theory of environmental meaning. He splits the notion of schemata into two kinds of knowledge explicitly. One is the linkage from the light pattern of the object to the object notion in the brain. The other is the linkage from the object notion to its potential usage.

With more biological support, Lam (1992) explains the visual perception as “an active information-seeking process directed and interpreted by the brain”, which contains three processing stages between four notions (Fig.2.1-2).

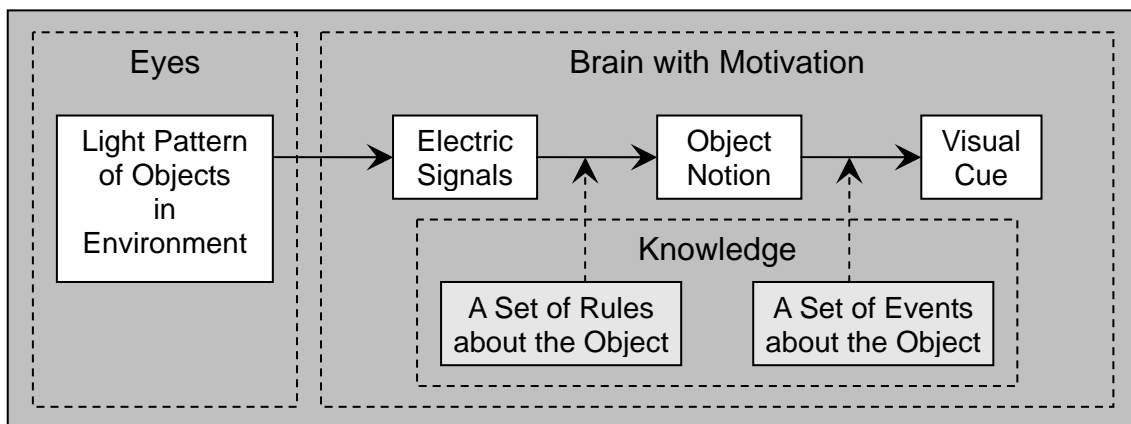


Figure 2.1-2 Visual perception process for the visual cue

The first stage, the exposure process of the film in the camera is a good metaphor of this stage. The light goes through the lens of the eye, and arrives at a set of nerve cells on the retina, which can be understood as the exposal particles on the film. There, the energy of the light is transformed into electrical signals sent to the brain through the optic nervous system. (These signals are explained as the visual stimuli in the Gibson’s model.) For example, when an evacuee sees a door painted in red, the light including the red rays from the door and the others from the other objects arrives at the retina of the evacuee. Then it is sent to the brain as electrical signals.

The next stage is called attributive stage. The brain classifies the electrical signals into object notion by the recognizable patterns, which depends on the existing associations between the patterns and the notions learnt through out the individual’s whole life. (These associations are explained as the schemata by Gibson and the first linkage from the light pattern of the object to the object notion by Hershberger.) In the above example, the pattern of the red light presented in the electrical signal can be recognized as an exit door by the brain, if the evacuee has the experiences or knowledge that the exit doors in public buildings are painted in red. Then the brain assigns the notion of “an exit door” to the red light pattern according to the existing association between the special red light pattern and the exit notion. If the evacuee hasn’t such knowledge, he will not recognize it as an exit at all.

The last stage is called expectant stage. The brain establishes another kind of associations between the object notion and its related event. (These associations are explained as the schemata by Gibson and the second linkage from the object notion to the potential usage by Hershberger.) If the event does happen as in the expectation, both the two kinds of associations are strengthened. Otherwise, they are weakened. Again in the above example, the association will be established between the notion of exit door and an event of going through it to the safety in the context of evacuation. If the door is an exit door indeed when the evacuee goes through it successfully, the association between special red light pattern and exit notion, and the association between the exit notion and the event of going through will be strengthened, which means the evacuee will have more confidence to recognize a special red light pattern as an exit and to use it to evacuate next time. In contrast, if he discovers the door a normal one, the association between the special red light pattern and the exit notion will be weakened. Or if he discovers the door blocked, the association between the exit notion and the event of going through will also be weakened. Next time he will have a less confidence either to recognize a special red light pattern as an exit or to use it in the evacuation.

Furthermore, the selective nature of perception (Lam, 1992) has to be considered. With tons of information available through the vision, human beings only process the interesting one according to the current context or his demands. In the above example, the individual will notice the special red light pattern as the exit only in the evacuation context, and he will ignore the other objects nothing to do with the evacuation, such as a chair, which could be noticed when he wants to sit. Meanwhile, one object might be perceived in different context with different notion with event associated.

In summary, the process relies on the two kinds of knowledge, so-called associations in Lam's explanation. One is between the recognizable light pattern and an object notion. The other is between such an object notion and the related event. After such a process, a kind of information hints the specific events or usage of this object is perceived according to the context tightly, which is actually the traditional notion of Cue central in the visual perception in the literatures (Ittelson, 1960).

3) Definition of Visual Cue

From the visual perception process introduced above, it is deduced that a visual cue is supported by two kinds of knowledge corresponding to the two kinds of associations introduced in the previous section. One kind of knowledge is a set of rules defining an object notion, which enables the special light pattern to be recognized as an object in brain. For example, the visual cue of a door must be supported by the knowledge as a set of rules to define what the notion of a door is, such as:

- A rectangular plane can be opened and closed;
- Its height is from the floor to a level above the head;
- Its width is wide enough to hold an individual;

...

The other kind of knowledge is a set of related events that can happen hinted by the cue, which also relates to the individual expectation on the cue. For example, the visual cue of a door must be supported by the knowledge as two related events:

- It can enable the individual to go from one space to the other;
- It can stop the individual going from one space to the other.

Supported by the above two kinds of knowledge, the visual cue acts as the media between the world and the human being's environmental behavior. As argued by Rapoport (1982), the visual cue-based communication between the human beings and the environment supports the decision making in the human behavior. The evacuation behavior can't be an exception.

In the book *Perception of Space and Motion*, Cutting and Vishton (1995) explain the concept of "cue", "The term 'cue' comes from sixteenth century theater documentation, and the abbreviation q, for quando, is Latin for when. As appropriated by psychology, but continuing theatrical play, a cue entails a knowledgeable observer, one with foreknowledge about when and how to act on layout information. The term cue, then, is heavily aligned with an empiricist position in any nativist-empiricist debates about layout. The way-finding researchers define this term as a source of information, which indicates their neutral position in the debate." In this research context, the same definition as the way-finding researchers' is accepted in principle. In addition, in the context of evacuation the definition of a visual cue is explicitly completed as:

A source of information, which offers a hint to a potential egress direction and can only be

perceived and used by the individuals with the two kinds of knowledge: One is a set of rules to define the object notion. The other is a set of events or usages related to the object notion.

In summary, it is the visual cue that enables the evacuees to understand the environment to make decisions along the egress route. To build a computational model, this research has to define what kinds of visual cues are interesting to the evacuees, define both two kinds of knowledge for each cue, and find a way to use the knowledge in the computational model. In the following section, the various visual cues are discussed in the context of evacuation.

2.1.3 Various Visual Cues

Arthur and Passini (1992) warn the designers, “The outworn but still prevailing notion is that architects design buildings, while graphic designers come along at the end of the building process and install some signs, and that the public is somehow helped by this.” Then, they suggest, “Providing the relevant way-finding information in the environment is an issue both in architectural and in graphic design.” And a “Spatial planning” with the specific concern on way-finding should be implemented before any other way-finding design issues, such as the sign. More sharply, Carpman and Grant (2002) warn the designers, “Never consider the way-finding only as a signage issue.” These voices all suggest all kinds of the elements in the environment offering the hints for the way-finding behavior should be carefully designed. An integrated view of the cues for way-finding, as well as evacuation is needed.

Many literatures try to give such a view of the various visual cues in the context of way-finding. Passini (1984) argues, “Signs, maps, verbal descriptions, as well as architectural and urban space can be seen as information support systems to way-finding.” Later, Arthur and Passini (1990) suggest, “In order to reach a destination, people must make decisions based on information that may be: verbal (notably the information desk); graphic (signs, symbols, directories, maps); architectural (entrances, stairs, elevators, corridors, doors, textures, sound); spatial (how things relate spatially to each other).” They also conclude two major physical factors causing the difficulty of way-finding as “the layout of the setting (The layout is defined by its spatial content, its form, its organization, and its circulation.) and the quality of the environmental communication (It includes all the architectural, audible, graphic expressions that provide the essential information for way-finding.)”. And explicitly they mention, “There is no guarantee that signage alone will lead to destination. Other alternatives must often be sought.”

With a clearer framework, Rapoport (1982) gives a systematic view of the various visual cues in the context of way-finding. He classifies them into three categories: Non-fixed Cues, Semi-fixed Cues, and Fixed Cues.

The above system is also inherited by the various visual cues in the context of evacuation, which almost covers all the mentioned cue types in the other literatures, except that the audio cue, such as the broadcasting and conversation with the staff, is not included according to the visual perception centered evacuation context. Additionally, it is suggested that the category of Non-fixed cues includes the threatening cues, such as the perceived fire or smoke. In the following paragraph, the various cues inherited from the way-finding context to the evacuation context will be discussed according to this framework.

1) Non-fixed Cues

In the evacuation context, Non-fixed Cues are defined as a type of information perceived from the dynamic objects offering the hint about the egress direction in the environment. It generally includes the threatening cues and the other evacuees' behavior cues.

a. Threatening Cues

The threatening cue is the information about where is the danger, which the evacuees can try to avoid spatially, such as the fire and smoke spread information. Nowadays, the computer fluid dynamics models can simulate the spread of fire and smoke according to the environment settings, which has become part of the evacuation simulation model and provides the threatening cues to the simulated evacuees, such as CRISP. Some other models, such as ASERI, BuildingEXODUS, EXITT, Legion, ALLSAFE, EGRESS, EXIT89, BGRAF, EvacSim, EgressPro, BFIRES-2, E-SCAPE, can use the threatening cues about fire and smoke input by the user (Kuligowski & Peacock, 2005).

b. Other Evacuees' Behavior Cues

The other evacuees' behavior cue is the information about how the other evacuees around the individual take actions to the emergency, which stimulates or constrains the individual's behavior. As a kind of social animal, human being's behavior can be influenced physically and psychologically by the others around him greatly, which involves a sets of phenomena. There are a rich set of researches and models on this topic in the field of pedestrian modeling, such as PEDflow (Kukla et al., 2001), PEDROUTE (Halcrow, 2002a), PAXPORT (Halcrow, 2002b), SimPed (Daamen & Hoogendoorn, 2002), NOMAD (Hoogendoorn & Bovy, 2002), and Legion (Still, 2000).

The social distances model described in Hall's two books: *The Silent Language* (1959) and *The Hidden Dimension* (1966) may be the first theoretical model to explain the various distances kept psychologically by human beings between each other in the social life and how these distances change in different context. From this theory, Was, Gudowskil, and Matuszyk (2006) develop their pedestrian model in the context of passenger movement in a train.

Another important phenomenon of human beings' influences to each other is queuing or congesting. This phenomenon is based on the researches on the relationships of the pedestrian flow, their walking speed and their density, which is studied precisely by Hankin and Wright, Haight, Breiman (Lovas, 1994). From these early explorations, Lovas (1994) develops the queue network model for the evacuation model EVACSIM, in which the rooms and doors are defined as nodes and links, and the movement from one node to the other through the link is treated as one queuing unit. Notably, there is a random waiting time assigned to every individual in queuing besides the moving time according to the flow-density functions. With the similar queuing algorithm, another pedestrian model NOMAD is developed (Hoogendoorn & Bovy, 2004), with which a "zipper effect" is discovered that "for a unidirectional flow, the bottleneck capacity will not be a linear function of the bottleneck width, but will increase in a stepwise manner" (qtd. in Hoogendoorn & Daamen, 2005). Such a discovery contributes to the flow prediction of the evacuation simulation against the general design guidelines suggested by Weidmann (Hoogendoorn & Daamen, 2005).

With a different view to the congestion, the phenomenon of crowding is another topic in this field. Asch is perhaps the first researcher to reveal the individual's tendency to follow the majority (Hostikka et al., 2007). In contrast, Moscovici, Lage and Naffrechoux (Hostikka et al., 2007) argue that it is the consistent minority who influences the majority. Notably, Schadschneider (2001) develops the floor field model to reproduce such a collective phenomenon, in which the crowd searches the route according to both the static and the dynamic information stored in the floor cells. The static one provides the information about the environment such as the nearest exit. The dynamic one is the virtual traces left by every passenger. Another important model in this field is Helbing, Farkas, and Vicsek's (2000) social force model. It interprets the crowd phenomenon as a mixture of the individualistic behavior and the collective herding instinct, in which "individualism allows some people to detect the exits and herding guarantees that successful solutions are imitated by the others." With this model, Helbing is able to reproduce the panic patterns, calculate the dangerous crowd pressures, and predict the congestions for different lane shapes. Similarly, the Multi-Agent Simulation for Crisis Management (MASCM) models the crowd phenomenon with a paired concept: the leaders and the followers (Santos & Aguirre, 2004). However, all the models involving such a concept have to answer two questions: How to decide who is the leader? Then, how does the leader behave independently? Obviously, the latter question is out of the field of the other evacuees' behavior cue. The leader has to find other kinds of cues to search his way.

2) Semi-fixed Cues

In the evacuation context, Semi-fixed Cue is a type of information perceived from the decorative objects offering the hint about the egress direction in the environment. These objects are setup in the environment temporarily and easy to reconstruct, such as the signage, the maps, and the different kinds of decoration (colors, materials, textures and lumination etc.).

Although all the above semi-fixed cues are discussed in the way-finding context, especially as a set of design guidelines (Arthur & Passini, 1992; Nassar & Al-Kaisy, 2008), there are a very few models explaining how these kinds of cues influence the individuals' behavior. For example, Xie's et al. (2005) model with a concept of the Visibility Catchment Area (VCA) tries to explain that how the distance from the observer to the sign influences the route choice in the evacuation, which is included by the popular evacuation simulation tool buildingExodus. Furthermore, Nassar and Al-Kaisy (2008) extend the variables of the sign perception to the divergence angle, the legibility zone, the expected walking speed, the location of the obstruction when the individual arrives at the legibility zone, the size of the obstruction, and the individual traffic volumes and directions of travel. With these variables, his model can estimate the probability of a sign being perceived through an artificial sight.

3) Fixed Cues (Architectural Cues)

In the evacuation context, Fixed Cue is a type of information perceived from the architectural forms offering the hint about the egress direction in the environment. These forms are the fundament of the environment and not easy to reconstruct. Thus, it is also called architectural cue, which includes global architectural cue and local architectural cue.

a. Prevalent Existence

The prevalent architectural forms offer the architectural cues, which can be perceived by human

Architectural Cue Model in Evacuation Simulation for Underground Space Design

beings and influence their behavior. There is a consensus on this argument in various professions.

Winston Churchill's statement in Parliamentary speech 1943, "We shape our buildings, and afterwards our buildings shape us", might be the most famous one outside the architectural profession. Another interesting one is Philip Johnson's comment, "Architecture is the art of how to waste space", from the view of a journalist of New York Times (qtd. in Lawson, 2001). In fact, he means that a real architecture contains more spaces used to influence the users' behavior than the spaces used to hold only the activities.

Without repeating the importance of the global and local architectural cues in the way-finding theory, there are more comments from the inside of architectural profession. Baum and Valins (1977) argue, "Whatever else our data suggests, we feel that one conclusion must be drawn from these data that the architectural design of human environments can have an influence on mood and behavior." Giving an example, Hershberger (1980) argues, "There are few forms in architecture to which men do not attach some meaning either by way of convention, use, purpose, or value. This includes the very mundane realization that a wood panel approximately three feet wide by seven feet high is a Door, which can be used to go through from one space to the other." From a social view, Hillier (1996) regards the social purpose oriented configuration as the primary nature of the built environment, which can influence the users' social behavior. With a metaphor of languages, Zevi (1993) regards the feature of the architecture from the other art forms as its working with the "three-dimensional vocabulary" related to the human being's behavior. Furthermore, In Lawson's (2001) book *The Language of Space*, the architectural cue is named as "the signal from the designed environment", which tells the people how to behave properly and suggest or invite appropriate behavior.

b. Important Functions

The global and local architectural cues take an important function in human being's life. They serve as the media between the built environment and the human cognition, the linkage between the architects and the users, and the contribution to the feeling of security.

Just like the other visual cues mentioned in the perception process (Section 2.1.2), the architectural cue is a media, through which the light pattern of the built environment is cognized by the human beings and invites their following behavior. Rapoport (1982) in his book *The Meaning of the Built Environment* comments argues, "The human mind basically works by trying to impose meaning on the world through the use of cognitive taxonomies, categories, and schemata, and built forms, like other aspects of material culture, that are physical expressions of these schemata and domains." Thus, the architectural cue with meaning is necessary for the human beings to understand the built environment.

Being the media between the human beings and the built environment, the architectural cue must be the object of the architects' manipulation. Furthermore, it is regarded as a kind of "Code" communicating the architect's "Intention" to the users in the designed environment (Hershberger, 1980). Naturally, the way-finding researchers also use it to build the legible designs (O'Neill, 1991a; Weisman, 1981).

Moreover, the architectural cue can contribute to the human beings' feeling of security. Lawson (2001) argues that human beings have a deep and fundamental need for a degree of stability, continuity and predictability in their lives. If the perceived architectural cue is encoded by the

architect in a way which is different from the way the user decodes it, the user will be confused or behave in an unexpected way. An occasional mismatch might be a surprise. However, more mismatches will make the user anxious.

c. Abstract Form

The global and local architectural cues are based on the architectural form in abstract. Human beings always perceive the architectural form with other kinds of visual cues in the real life. To eliminate the interference from the other cues, the architects always use special visualization methods to present the architectural form in abstract, such as the bubble network for the space organization design, the two-dimensional planes and sections in lines for scale design, etc. To study the architectural cues, this research has to find a proper way to present the abstract architectural form.

It is the abstract three-dimensional geometric feature of the architectural form that offers the architectural cue. Ching (1996) argues, "Architectural form is the point of contact between mass and space...Architectural forms, textures, materials, modulation of light and shade, color, all combine to inject a quality or spirit that articulates space." Meanwhile, Le Corbusier (1931/1986) points out the importance of the three-dimensional geometric features of the architectural form to the visual perceptions. Thus, the abstract three-dimensional geometric feature is the fundamental property of the architectural form, and it can be independent from the other properties, such as textures, materials, modulation of light and shade, and color. A door is still a door when its texture, material, and all the other attributes are changed greatly. While a door might never be a door, when its three-dimensional geometric feature changes.

d. Global and Local

There are generally two kinds of architectural cues working differently in evacuation behavior. As argued by Passini (1984), one kind of architectural cue is used in way-finding with a decision plan, while the other kind of architectural cue is used in the dynamic way-finding. They relate to the two redefined Weisman's way-finding strategies (Section 2.1.1).

In way-finding with a decision plan, the individual must have the architectural cue about the environment globally. In other words he must be familiar with the environment as a system in some extent. Based on such a cue, the general way-finding task can be broken into a set of sequential manageable sub-tasks, each of which can be referred to a portion of the cue. As a plan, all these sub-tasks are generated and remembered by the individual before he sets out. Then the only thing he has to do in the way-finding is to follow this plan sequentially. Such an architectural cue is defined as the global architectural cue.

In dynamic way-finding, the individual hasn't the global architectural cue of the environment. In other words he is unfamiliar with the environment. As a result, he can't make a plan to follow before he sets out. He has to collect new information along his trip gradually. His decision making process is regarded as an ongoing process. Such information perceived locally along the trip is defined as the local architectural cue.

In summary, Fixed Cue or the architecture cue include the global architectural cue and the local architectural cue. They both prevalently exist in the environment and used in the way-finding process, as well as the route searching process in evacuation. They are perceived from the abstract

three-dimensional geometric feature of the architectural form, and they lead to two distinguished main areas of the researches on the way-finding in architectural spaces, just as mentioned by Werner and Schindler (2004). These two: the global architectural cue and the local architectural cue are going to be discussed separately in the following sections.

e. Global Architectural Cues

The global architectural cues are perceived from the architectural forms and offer information about how the parts of the building are organized globally, which has an important relationship to either Tolman's notion of Cognitive Map in 1948 or Lynch's notion of Mental Image in 1960. (Weisman uses the both notions similarly in the way-finding strategy.) There are two common ways to form the cognitive map or mental image either by traveling the space or by overlooking a vantage point, via some symbolic, analog, iconic modeling (Golledge, 1999a). Obviously, the latter way to form the cognitive map or mental image depends on the perception of some other non-architectural cues such as the perception from the maps. Thus, the global architectural cue is regarded as only one of the sources to form the cognitive map or mental map, which is perceived through the traveling in the space.

Four Main Information Sources

Generally speaking, there are four types of sources to provide the global architectural cues. They are: the circulation system, the exterior form of the building, the visible structural frameworks, and the atrium.

As argued by Arthur and Passini (1992), the nature of the architectural circulation system is the spatial characteristics of a site, and the understanding of it is the most useful for efficient way-finding. Generally the architectural circulation has been classified into four categories: Linear circulations, Centralized circulations, Network circulations (Scatter-point network, Grid network, Hierarchical network), and Composite circulations. After the individual travels in the space through a part of the circulation system, he would understand the typology of the system and be able to guess the global spatial organization.

Confined by the circulation system, the exterior building form always reflects the inner space organization. Arthur and Passini (1990) also argue that before the individual enters the building, the exterior building form always gives the first impression of the layout of the spaces inside. For example, the form of a flat slab hints a linear circulation system, while the form of a tower hints a centralized circulation system.

Similarly, the visible structural framework inside the space also hints the logic of the spatial organization. Werner and Schindler (2004) conclude that the axis reflected by the structural framework provides the spatial information about the symmetry, the elongation, the functional characteristics etc. For example, the structural symmetry of two spaces always hints the similar functions of them.

Moreover, the atrium offers a great opportunity for the individual to have an overview from the inside on the spatial organization. Passini (1984) argues that the buildings containing a central open space are generally well understood and lead to clear sketch maps. Such an opening gives visual access to the different floors of the building and allows one to sense at least part of the building's volume. A single perspective of the space contains more information than the one in a closed floor

arrangement, in which the global understanding has to be learned from a number of separate trips at different floors.

Beside the above information sources, there are many factors influencing the perception of the global architectural cues in some extent. They are introduced in the following with the related researches.

Researches

Undoubtedly Lynch (1960) is the first researcher to investigate the relationship between the spatial organization and the way-finding performance through the notion of legibility. Since then, some researchers try to reveal this relationship quantitatively by measuring the complexity of the floor layout (Weisman, 1981; Passini, 1984; Peponis, Zimring, & Choi, 1990; O'Neill, 1991a; Werner & Schindler, 2004). Some researchers try to find how the features of a plan can influence the way-finding performance, such as Baskaya, Wilson, and Ozcan (2004) revealing that the asymmetrical setting correlates to less error in the mental map generation. Notably, Hillier's (1996) space syntax is the most influential one among them, in which the spatial organization is represented by a set of computational maps, such as the axis map, the visual graph map, the connectivity map etc. Each map reflects one feature of the spatial organization. However, Werner and Schindler (2004) argue that such measurement on the complexity of the figural entity assumes its perception as an overview of the whole large space. In contrast, the individual's perception happens in the part of it sequentially. To distinguish the two kinds of complexities at the different scales, some researchers turn to the formal geometrical analyses method (Peponis et al., 1998; Peponis & Wineman, 2002; Peponis et al., 2003). However, Werner again gives further comments on the lack of orientation acknowledgement for these formal geometrical analyses methods.

Just as the other way-finding researches, some competence-oriented researches are developed based on the above performance-oriented researches. Based on Lynch's five elements of spatial organization, Kuipers' (1977; 1978) TOUR model is regarded as the first competence model for way-finding reasoning, in which the cognitive map of the environment is represented by five data structures, and the way-finding problem can be calculated based on them. Similarly, Penn and Turner (2001) develop the pedestrian model on the visual graph concept of Hillier's space syntax.

In summary, the investigation of the global architectural cues begins with the way-finding problem raised by Lynch, which indicates its important position in this area. Furthermore, there have been many performance-oriented theories, as well as a rich set of competence-oriented models. However, just as introduced, the spatial organization representation is suggested to receive more concentration on the sequential individual perception in the parts of the space, which leads to the necessity of investigating the local architectural cues.

f. Local Architectural Cues

In the context of evacuation, the local architectural cue is a type of information that is perceived from the architectural forms and hints the evacuation direction based on the abstract three-dimensional geometric features of the local architectural elements, such as doorway entrances, stairs, exits etc. As the example mentioned in the introduction of the visual perception process (Section 2.1.2), the architectural elements can hint their usages everywhere. A similar example about the architectural element of the door having the hint to the behavior of passing through is also used by Passini (1984). Furthermore, he explains that the special design of a door even can tell the

Architectural Cue Model in Evacuation Simulation for Underground Space Design

individual whether it is used for public or private. It is something also argued by Arthur and Passini (1992) that through the cue, the architectural element can express itself without a sign. He gives another example, in which a door in the middle of a symmetrical façade is easily recognized as the main entrance without any sign to indicate.

Four Main Information Sources

Generally speaking, there are also four types of sources to offer the local architectural cues. They are: the type of the architectural element in the circulation system, the feature of distance from the architectural elements to the individual, the feature of the scale of the architectural element, the feature of the angular positions of the architectural elements in the individual's view.

Similar to the global architectural cue, the local architectural cue has a tight relationship to the architectural circulation system in the way-finding context. Arthur and Passini (1992) define four types of the architectural elements offering the local architectural cues about the circulation system. They are: the "entrance" indicating where to enter and leave the building normally, the "exit" indicating where to leave the building in emergency, the "path" indicating where to enter the other space, and the "vertical access" indicating where to go to the other levels of the building. Thus, the type of the architectural element can offer different hints on its usage.

Additionally, Lawson (2001) argues that the distance feature from the architectural element to the individual can express the local architectural cues. For example, between two similar entrances on the façade, the individual can feel the hint of entering much stronger from the entrance in a closer distance.

Similarly, Lawson (2001) argues that the scale feature of the architectural element can express the local architectural cues. Taking the two entrances as example again, between two entrances with obvious difference in the scale, the individual can easily recognize the main entrance in the bigger scale.

Moreover, limited by human beings' view field, the angular position feature of the architectural elements in the view field can also express the local architectural cues. In Bryan's experiment (Ozel, 1987), more than half the cues remembered by the participants are the cues in the view center. In Arthur and Passini's research (1992), the legibility of entrances and exits is affected by the angle of approach. In Dalton's experiment (2001), the way-finding decisions strongly correlate to the maximum angles of the incidence of the road-center-lines leading from a junction.

Researches

Based on the results of the above performance-oriented researches, several competence-oriented researches are introduced in the following. With the information source of the distance features, a pedestrian model simulating the way-finding behavior in relaxation is built (Turner & Penn, 2002; Penn & Turner 2003), in which the agent is always seeking a path leading to a distant space with its artificial vision in every three steps. With the information source of the scale features, an evacuation model especially for the stair usage is built (Cheung & Lam, 1998), in which the difference height of the stair is the main variable to the agent's choice. With the information source of the angular position features, Turner (2000) builds a pedestrian model, in which the agent travels from point A to B through as few turns as possible rather than through the shortest distance.

Besides the models exploring one specific information source of the local architectural cues, some other models try to integrate the local architectural cues into one variable to drive the behavior. Ozel (1987) builds the evacuation model BGRAF with a subjective usage of the local architectural cues, in which the expert can assign a value called the architectural preference level to every architectural element, and the agent will follow the evacuation direction indicated by the architectural element with higher architectural preference level. It is the expert who decides where to provide the local architectural cues and in what extent. Similarly, a formal model for the way-finding process is built based on Gibson's concept of affordance and schemata, in which the different attraction of the architectural elements are set by the experts again into three levels: good, poor and none. The agent follows the "Cue-Choice" process to perceive and to choose the cues according its levels (Raubal & Egenhofer, 1998; Raubal & Worboys, 1999).

In summary, the local architectural cues, as well as other kinds of cues, lead to the prevalence and diversity of the visual cues, all of which can contribute to the evacuees' decision on how to search the route to the safety. However, with so many cues available simultaneously, does the evacuee really feel the decision making much easier, or even harder?

2.1.4 Convinced or Confused by Cues

With so many visual cues, the decision maker feels sometimes convinced, while sometimes confused. As mentioned in the visual perception process (Section 2.1.2), the human being depends on two kinds of knowledge to make use of cues. One is a set of rules defining an object notion, which enables the special light pattern to be recognized as an object in brain. The other is a set of related events that can happen hinted by the object notion. Both kinds of knowledge also form the expectation in the final stage of the process, which can influence the existing knowledge and the emotion status greatly. Lam (1992) argues, "We can survive and function only because the world usually behaves and appears as we expect it to." Taking the example of the door again, a person might feel surprising when he opens it, which leads to a blocking wall rather than another space. In contrast, it is believed that he will feel anxious in such a circumstance during the evacuation. Obviously, the human beings feel confused with the visual cues working differently from their expectation (Lam, 1992), which always leads to more stress in the way-finding or the evacuation context (Zimring, 1982). Vice versa, the stress can be reduced through the visual cues fulfilling their expectations (Zimring, 1982; Arthur & Passini, 1992). With such a view, it is obviously important to keep the visual cue working within the human beings' expectation in the evacuation context. Undoubtedly this is the job of all the visual cue designers. They have to be sure about two things: One is whether the visual cue designed by them works in a way just as they planned. The other is whether all the visual cues work coherently not conflicting to each other.

1) Designing Cues to Work as Planned

There are three properties of the visual cues influencing their coherences between the designers and the users. They are: the context property, the social property, the role property.

The context property defines what situation the human beings are in. As mentioned in the visual perception process (Section 2.1.2), the human being's visual perception is selective according to his interest or motivation. Obviously, the interest is influenced by the context greatly. For example, the exit door will not be an interest to a person in relaxation. However, it must be an interest object to an evacuee. Thus, a cue must relate to at least one planned context (Lawson, 2001), in which an

expectation from the observer must be clearly understood by the designer.

The social property defines what society the observer belongs to. There is a consensus that different expectations on the same cue can be held by the persons from the different societies (Hall, 1966; Lym, 1980; Rapoport, 1982).

The role property defines what role the observer acts. For example, many researchers mentioned the different feeling or emotion received from the same architectural design by the different roles, which means they have different expectations from the visual cues. Rapoport (1982) argues that one of the hall marks of man-environment research is the realization that designers and users are very different in their reactions to the environments, their preferences, and so on, partly because their schemata vary. Deasy and Lasswell (1985) argue that the feeling and emotion that a building communicates to the general public is frequently quite different from the feeling or emotion that it communicates to the designers. Furthermore, he suggests dividing the general public into two groups. One is the users of the building who are so familiar with it. The other is the visitors of the building who are not familiar with it. Lawson (2001) argues that the architects as a group think about the architecture in a distinctly different way to the rest of humanity. Carpman and Grant (2002) reveal the different way-finding expectations among users, staffs and administrators.

With all these three properties considered carefully, the visual cue is still not able to influence the individual's decision in a planned way for sure, if the information from some visual cues is conflictive to each other.

2) Keeping Cues Working Coherently

There is always a debate on which kind of visual cue is more important than the others in the way-finding context, or sometimes in the evacuation context. Through the experiments, Bryan reports that only a mere 7-8% people reported noticing exit signage during emergency egress (Ozel, 1987). Arthur and Passini (1992) argue that it is hard and useless for the graphic designers to build a color code system to solve the architectural problems, such as the various split-levels, the confusing spatial organization, the ambiguous circulation pattern, the repetitive architectural features, the contradictory articulation of the interior and the exterior. Furthermore, he concludes that the architectural cues are much more fundamental than the graphic signs.

It is not necessary to join the debate. The view of this thesis shared by Lynch (1960) and Lawson (2001) is that the prevalent various visual cues are all important to the diversity of the human beings for different contexts, different societies and different roles. Such a redundancy of the visual cues is necessary to make the space readable and understandable. It is also believed that based on every cue working in a way as planned, the redundant visual cues pointing to the same spatial direction must work coherently in the way-finding context. Otherwise, any conflict between these redundant cues will result in confusion on the pointed direction. For example, the following is a view of a New York subway station platform in underground (Fig.2.1-3). In the context of underground evacuation, the confusion on the potential action to go downstairs can be perceived through the conflict between the semi-fixed cue (a sign pointing to the exit as a safe place) and the local architectural cue (a down-stair leading to the deeper underground space away from the safe ground level).



Figure 2.1-3 Conflict between the redundant visual cues

In summary, designers have to understand how their cues really work and collaborate with the other designers to keep all kinds of cues work coherently. However, there are more issues than these. With every cue working well individually and integratedly in the evacuation context, there will be still several potential egress directions hinted by several cues or several groups of the redundant cues. For example, the confusing cue group mentioned previously hints one egress direction to go downstairs. Another redundant cue group, including the further exit sign and the right turning doorway entrance, hints another egress direction (Fig.2.1-3). These two hinted directions do not conflict to each other, but offer different choices to the evacuees. According to the evacuation process discussed in Section 2.1.1, the evacuees will make a choice among these alternatives to take one direction for the next step. In the following section, two general models of decision making are introduced.

2.1.5 Decision Making with Cues

The “Cue-Choice” model is introduced in Section 2.1.1 to reveal the process how the evacuees use the visual cues to search the route to the safety, in which the evacuees perceive the various visual cues and have to make a choice among them to decide the egress direction for the next step. Generally speaking, there are two kinds of decision making model explaining how the choice is made by the human beings in their behavior according. One is called Utility Maximizing Model. The other is called Computational Process Model. (Arentze & Timmermans, 2000)

1) Utility Maximizing Model

As explained by Arentze and Timmermans (2000), Utility Maximizing Model is based on the assumption that choice alternatives can be represented as bundles of attribute levels. Individuals are assumed to derive some utility from these attribute values, and combine these part-worth utilities into some overall measure of utility according to some simple algebraic rule. Because of the measurement errors and the taste variation, these utilities are assumed to consist of a systematic measurable component and a random component. With such an assumption, the choice probabilities can be derived. A commonly made assumption is that these random terms are independently and identically Gumbel distributed. Under this assumption, the choice probabilities are represented by the well-known multinomial logit model, which has been frequently used to predict mode and destination choices.

Architectural Cue Model in Evacuation Simulation for Underground Space Design

Since the mid 1970s, such a kind of decision making model has been used in many researches to measure and predict the human beings' preference on a set of choices. For example, some housing preference models are built in this framework (Orzechowski, 2004). Some route choice models for pedestrian are also built in this framework (Bovy & Stern, 1990; Verlander, 1997; Hoogendoorn & Bovy, 2004).

However, any model has its assumptions, which bring limitations to it. There are generally three assumptions received a lot of attentions from the opponents. They are: Free Choice, Finite Alternatives, and Irrelevant Alternatives.

a. Assumption of Free Choice

Utility Maximizing Model assumes that the individuals are free in choosing the alternative they like best. The opponents argue that it is unrealistic in some circumstances, in which some alternative does not exist in the reality at all (Arentze & Timmermans, 2000). As a result, whether all the alternatives are realistic should be examined before the application of the model.

b. Assumption of Finite Alternatives

Utility Maximizing Model assumes that the choice set contains finite alternatives. Although some researchers try to apply this model to the pedestrian's route choice (Hamacher & Tjandra, 2001; Hoogendoorn & Bovy, 2005), it is warned that the realistic route choices in space for the pedestrian are infinite (Hoogendoorn & Bovy, 2005). As a result, whether the number of the alternatives is finite should also be examined before the application of the model.

c. Assumption of Irrelevant Alternatives

Utility Maximizing Model assumes that the alternatives are irrelevant to each other, which means there should not be nested alternatives. When a new alternative is added to the choice set, it will detract market shares from all the existing alternatives in proportion to the original values. If the new alternative has a relation to any of the original alternatives, such assumption becomes unreasonable (Arentze & Timmermans, 2000). The classical example is the blue-red bus problem. The citizen can choose one of the two transportation tools: the train and the bus in blue. If they are hypothesized to both have 50% probability to be chosen, it will be unreasonable that both the train and the blue bus lose the same probability, when the third alternative, the car in red, is added to this choice set. As a result, whether the alternatives are irrelevant to each other should be examined before the application of the model. If the relationship exists, the solution called nested logit model can be used (Orzechowski, 2004).

2) Computational Process Model

The opponents of Utility Maximizing Model argue that the individuals do not always make decisions so rationally and have enough resources to evaluate all the utilities of the alternatives, especially when the number of the alternatives is huge or the evaluation itself takes a lot of time, energy or other resources. They prefer to use a heuristic process to find the acceptable alternative within an acceptable cost. As explained by Arentze and Timmermans (2000), Computational Process Model constitutes a powerful theoretical approach that conceptualizes choices as outcomes

of heuristics. Individuals are assumed to collect and constantly update their information about their environment, through their interaction and experience with the environment, and process this information to form opinions and develop imperfect and limited cognitive representations that are stored in their long-term memory. It forms the basis for a short-term memory, which contains a subset of imperfect information about the environment and sets of heuristics. Thus, in its most basic form, a production system is simply a set of IF-THEN rules, a short-term memory (STM), and a mechanism for controlling which rule to apply in a given context.

Another kind of model with the bounded rationality is also located in this category, which reflects strategies that are used to successfully deal with conditions of limited time, knowledge, or computational capacity, including applications of heuristics such as recognition, take-the-best, trying something that worked before, and one-reason decision making (Gigerenzer, 2000).

In general, the above two kinds of the decision making models have different assumptions and are adapted to different choice problems. Utility Maximizing Model has the advantage to make predictions on the unseen alternatives. However it has several limitations according to its assumptions. Computational Process Model has the advantage to make choice with the limited resources relative to the large number of the alternatives or the difficult evaluation process. However it is difficult to make a judgment on the unseen alternative without a related rule in the model.

2.1.6 Summary

In this section, the evacuation process that the human being searches the route to the safety is introduced. As a kind of way-finding process, the evacuees can use three kinds of strategies in the “Cue-Choice” model, in which they perceive various visual cues to understand the built environment, and choose a cue or a group of cues for the egress direction hinted by it for the next step. The choosing process can be explained by the two kinds of decision making models according to the different contexts.

In the next section, such a process is refined into a more detailed one according to the research context, which tries to explain the process from an architectural view with more considerations on the space design of complex public underground environment.

2.2 Evacuating in Complex Public Underground Space Design

In the previous section the process of the evacuees' searching the route to the safety is discussed in general. To build a model from the starting point of an architect-oriented application especially for such a process in the specific context of complex public underground space design, the general process has to be refined into a more specific one according to the architectural starting point. First, the nature of space design is discussed as such a starting point. Next, according to it, three issues are discussed, which distinguishes the refined process in the proposed specific model from the general one. They are: the limited architectural cue, the limited strategy, and the proper decision making model.

2.2.1 Nature of Space Design

As mentioned in the motivation (Section 1.1), the research behind the thesis starts from the demand of an architect-oriented application in the context of complex public underground space design. The nature of such a specific context is discussed in the following to clarify such an architect-oriented starting point behind the proposed model.

From architect's view, a "complex public underground space design" is a kind of space design especially for complex public underground environment. Furthermore, a "space design" is a kind of design on the architectural space. To Bruno Zevi, architectural space is a uniformly extended material, which can be modeled in various ways (Norberg-Schulz, 1971). Following his idea, the design on the architectural space is regarded as the manipulation of three generic types of planes or interface, namely Overhead Plane, Wall Plane, and Base Plane (Ching & Francis, 1996). Similarly, Netsch defines the notion of space design as a systematic development of three-dimensional patterns of geometrical character. In brief, "space design" is regarded as a kind of architectural design, in which architect configures the geometric character of the environment interfaces, such as space topology, space dimension, position of circulation elements, and etc.

Being at a very beginning stage in the whole design process, space design does not include explicit configurations of other design issues, such as structure system, material, color, texture, light, sign, occupant density and etc, although it has probably contained some rough considerations on these issues. Being the carrier of the other issues, space design has to be firstly composed. Only after that, architect can develop, evaluate, and modify the configurations of other design issues embedded in the space design again and again in the following design process. For example, in the design of an opera house, a space design like a horseshoe is always firstly composed with the geometric dimensions before any other design issues, such as structure system of wall and ceiling, material of ground, color of the seats and so on.

As such a fundamental issue, space design has to be very carefully configured to avoid big changes in later design stage. Such changes always come with ripple effect in almost all the other issues, which means that a lot of previous efforts are wasted and more efforts are needed in the future. Being practical, sometimes architect decides to use other design issues to patch the problematic space design. For example, in an opera house design again, many sound reflection panels will be added to the design to improve the poor audio quality caused by an awful geometric dimension of the space design. Unfortunately, in the context of evacuation, such awful space designs may cause serious results, if the other design issues take no effect or bring more confusion to evacuees.

In summary, a “complex public underground space design” is a kind of space design, in which architect explicitly configures the geometric character of the interface of complex public underground environment. It includes the configuration of space topology, space dimension, and position of circulation elements. Other design issues are not composed in such a stage. In other words, in space design, only the architectural cues including the global one and the local one have been configured. The other kinds of cues (Section 2.1.3) have not been configured in this stage. Thus, in the context of complex public underground space design, only the global and local architectural cues are the input of the proposed model.

2.2.2 Limited Architectural Cue

It is argued that among the architectural cues as the input of the proposed model, the global architectural cue is hardly perceivable to the evacuees during their evacuation in complex public underground environment, although it has already been configured in its space design. As discussed previously, global architectural cues can be perceived through four information sources: the circulation system, the exterior form of the building, the visible structural frameworks, and the atrium.

Being complex means the space consists of several independent spaces designed by different architects for different functions through different layout principles. It is a multi-level, multi-function, multi-layout-pattern environment. Probably there will be a big difference of either the circulation systems or the structural systems between every independent space. It will be very difficult and risky to predict the global organization of the whole space according to the information from only one independent space. Similar comments are found in the literature. Furthermore, Arthur and Passini (1992) argue that the circulation system in the underground settings may be less well organized than in the normal buildings for structural and economic reasons. On the other hand, the way-finding task in the underground settings is difficult even if the circulation system is simple. Consequently, it is concluded that the circulation system and the structural system are not reliable to provide the global architectural cues during the evacuation in complex public underground environment.

Being underground means the space does not have any exterior building form at all and it is very rare to build an atrium in underground for both the structural reason and the economic reason (Carmody & Sterling, 1983). Consequently, it is concluded that the exterior building form and the atrium is not available to provide the global architectural cues during the evacuation in complex public underground environment.

Furthermore, Carmody and Sterling (1983) argue that the underground space lacks the spatial orientation naturally, which is fundamental to the perception and usage of the global architectural cues.

In summary, it is concluded that actually the global architectural cues configured in complex public underground space design are not perceivable to the evacuees during their evacuation. In contrast, the local architectural cues configured in complex public underground space design are still perceivable and usable. Thus, to build the proposed model from the architectural starting point, this research need to transit the qualitative definitions of the four information sources (Section 2.1.3) of local architectural cues into quantitative variables, which are the key influential factors of the evacuee’s behavior modeling in the context of complex public underground space design .

2.2.3 Limited Strategy

With the global architectural cues unperceivable, the evacuation strategies are also limited. In Section 2.1.1 three general evacuation strategies are discussed as the following:

1. The evacuee uses all the perceived cues to search the route to the safety without a plan or known destination.
2. The evacuee uses the cognitive map or mental image to plan and follow a route to the safety or a known destination.
3. The evacuee leaves the building through the same route as they enter.

With the unperceivable global architectural cues, the second and third strategies are not available in the process that the evacuees search the route to the safety.

According to the context of the space design, the other kinds of cues, such as Non-fixed Cue or Semi-fixed Cue, have not been designed yet. Thus, without the other cues, the mental image or cognitive map can only be derived from the global architectural cues perceived either through the previous visit or through the current visit (Golledge, 1999a). However, on the one hand, it is assumed that most of the evacuees in the complex public underground space as new visitors to avoid any risk. They do not have previous visiting experiences. On the other hand, there is no perceivable global architectural cue in the current visit according to the discussion in the above section. In one word, there is not any kind of cue to form the mental image or cognitive map, without which the evacuee can't use the second strategy to plan the route to the safety before he sets out.

Moreover, according to the context of a subway station, the space contains a big number of the visitors entering the space from the subway platform. They can't use the strategy three to turn back to the entrance in the evacuation. Although there is not a detailed report about how many percentage of the visitors entering the underground space from the platform directly, it must be a number that can't be ignored. Thus, it is assumed that the evacuees can't use the strategy three in this research context to avoid any risks, which means that the proposed model always predicts the worst situation.

In summary, with strategy two and three excluded, it is assumed that the evacuees only use the strategy one in this research context of the complex public underground space design.

2.2.4 Proper Decision Making Model

With the local architectural cues and the strategy one left in this research context, the general "Cue-Choice" evacuation process (Section 2.1.1) can be explained as a set of steps each with three phases:

1. The evacuee searches all the local architectural cues perceived from the environment.
2. The evacuee chooses one local architectural cue in a decision making process according to his preferences and knowledge.
3. The evacuee evacuates to the direction hinted by the chosen local architectural cue.

Now the question is which decision making model can explain the choosing process in the second phase, Utility Maximizing Model or Computational Process Model?

It is regarded that Utility Maximizing Model is the proper one to explain this choice behavior in the research context. The evacuees are still expected to behave rationally with the finite alternatives. The evacuees will perceive several local architectural cues, estimate their utilities according to their attributes, and make the rational choice for the cue with the maximizing utility. As just discussed in Section 2.1.3, the local architectural cues have four main information sources: the feature of the architectural element type, the feature of distance from the cue to the evacuee, the feature of the cue's scale, the feature of the cue's angular position in the view field. The number of the architectural element type is finite. If the continuous values of the distance, scale and angle are mapped into the different levels within the practical value ranges of the underground space design, a set of finite levels is available. As a result, the number of the alternatives is finite. Moreover, represented in three dimensional forms, all the types of the architectural elements can share the attributes of the distance, scale and angle. Thus there is not any local architectural cue unrealistic. Furthermore, the irrelevant alternative problem can be avoided by modeling the choosing behavior as a set of paired comparisons.

Utility Maximizing Model is selected not only for its suitability as the choosing framework, but also for its advantages. Although the alternatives of the local architectural cues are finite, it is impossible to measure all the preferences through experiments. Utility Maximizing Model allows using a relatively small set of alternatives according to the fractional factorial design technique (Montgomery, 1991) to measure the human preferences, with which it is possible to predict the preference for the local architectural cue never tested in the experiment. Such advantage is not supported by Computational Process Model.

In addition, it is believed that the alternatives in the evacuee's view are not so many, and the estimation process is based on the evacuee's instinct without any effort. The advantages of Computational Process Model in processing big number of alternatives and evaluating complex alternatives are not useful in this case.

In summary, Utility Maximizing Model is regarded as the proper framework to explain the evacuee's choosing process in the research context.

2.2.5 Summary

In this section, after the discussion on the architectural starting point from complex public underground space design, it is clarified that only the geometric characters of the environment interfaces governing the global and local architectural cues are the input of the proposed computational model, which aims to simulate the evacuee's route searching process according to the space design of complex public underground environment. With this clarification, three special issues are discussed. First, being hardly perceivable, global architectural cue during evacuation is excluded from the input of such a model. Next, with global architectural cue unperceivable during evacuation and other conservative assumptions, the route searching strategies of planning a route and returning to entrance are excluded from the model. Last, according a comparison with Computational Process Model, Utility Maximizing Model is selected as the choosing framework of the only strategy in the proposed model. Finally, the general evacuation process is refined into a more specific one, in which to search the route to the safety, the evacuee chooses the proper cue among the local architectural cues according to the utility maximizing principle to decide the egress direction for the next movement step by step.

2.3 Modeling Architectural Cues in Evacuation Simulation

In the previous section, evacuation behavior is discussed from the architectural view in the context of complex public underground space design. In this section, a brief introduction is first given on evacuation behavior researches. Next, 36 computer evacuation simulation models are discussed in the context of modeling architectural cues. Finally, the state of art in modeling on architectural cues is concluded.

2.3.1 A Brief Introduction on Evacuation Behavior Researches

Although evacuation is not restricted to emergency caused by fire, human behavior in fires is regarded the most important and prevalent evacuation behavior. Suggested by Ozel (1987), the first systematic study on such evacuation behavior is done by Wood. Following him, Bryan and Keating also study evacuation behavior through the post-facto investigations in a number of fire incidences. Other researchers, such as Pauls, try to do the study by means of designed fire drills.

Based on these field studies, several conceptual models are developed to explain how the evacuee behaves (Ozel, 1987). Lerup develops a model explaining the behavior as a series of interdependent bits called “episodes” separated by more or less abrupt changes. Bryan develops a six-step model explaining the behavior from when the evacuee recognizes the fire to when he tries to reassess his situation after the evacuation. Bickman, Edelman, and McDaniel develop a three-step loop model including the detection of cues, the definition of the situation, and coping behavior. Canter, Breaux, and Sime develop a model containing three phrases: recognition, action, and escape.

With the support from computer simulation, evacuation behavior research enters a new era of the computer-based evacuation behavior model. The goal of these researches is to build a model which when provided with suitable information can produce evacuation behavior hardly distinguishable from the behavior by human beings when they are provided with comparable information. With such models, it becomes safe, cheap and convenient to evaluate the evacuation performance of a hypothesized environment. As suggested by Ozel (1987), these models are the valuable prediction tools to the designers.

Stahl’s model BFIRE I (1979) might be the first computer evacuation model that truly aims at simulating the human behavior in fires. Later on, the researcher Berlin develops the so-called hydraulic model, which focuses on the physical dimension rather than the human behavior (Ozel, 1987). As Low (2000) introduces, the computer-based evacuation modeling has gone through three phases: the flow, the individual, and the group. In the first flow phase, the evacuees are treated as the flows of the homogeneous particles. In the next individual phase, the different individual characteristics are assigned to these particles. It means they can behave differently just as different real persons. In the third group phase, the individuals can be grouped according to their shared characteristics. The evacuation behavior is a mixture of the individualistic behavior and the collective herding instinct.

In summary, as an important direction of the evacuation behavior research, the computer-based evacuation behavior simulation still has a large unknown area comparing to its partner, the computer fluid dynamics simulation, in the evacuation simulation modeling. On the one hand, it is true that as the research object, the human being is much more complex and difficult to study than

the physical object of the fire process. On the other hand, it is such a difficulty that attracts more and more attentions and efforts to improve the computer-based evacuation behavior simulation. In the following, 36 computer-based evacuation simulation models are introduced in the context of this research. These models all contain an architectural cue-based sub-model for the evacuation behavior simulation, especially for the route searching process.

2.3.2 Architectural Cue Modeling in 36 Existing Evacuation Models

In this section, 36 evacuation simulation models are discussed in the context of this research. First a general introduction on these models is provided. Next, in this research context, the use of the architectural cues in these models is carefully studied.

1) A General Introduction

A classification always helps us to understand a large set of objects. Here some classifications on the evacuation simulation models are used to provide an overview.

According to the different computing approaches, Ozel (1987) classifies these models into three categories: the deterministic model, the stochastic model, and the expected value model. In the deterministic model, given a set of inputs, the evacuation simulation model with an analytical representation of the evacuation process will have a unique outcome. In the stochastic model, given a set of inputs, the evacuation simulation model with random chance parameters will have outcomes in a probability context. Furthermore, in the expected value model, the chance parameters are assigned to expected values or means.

According to the different aims, Gwynne et al. (1999) classifies these models into three categories: the optimization model, the simulation model, and the risk assessment model. In the optimizing model, treating the evacuees as a flow of homogeneous particles, the model can handle large size of people. The evacuees' behavior is assumed as efficient as possible, which means they will ignore peripheral and non-evacuation activities and take the shortest route to the nearest exit. In the simulation model, treating the evacuees as individuals, the model can predict the evacuation behavior more accurately and realistically. In the risk assessment model, running repeatedly, the model can statistically assess the risks of the designs.

According to the different modeling methods, Kuligowski and Peacock (2005) classify these models into three general categories: the behavioral model, the movement model, and the partial behavior model. The behavior models incorporate occupants performing actions to movement toward a specified goal. The movement models move the evacuees from one point to the other to reveal the potential congestions and bottlenecks. The partial behavior model is the mixture of the both. Furthermore, the behavior category is divided into four branches. The "implicit behavioral models" assign the response delay time or characteristic to the evacuee to influence their movement. The "conditional / rule-based behavioral models" influence the evacuees' movement by sets of conditions of the environment or rules in "if-then" logic. The "artificial intelligence behavioral models" use algorithms to behave intelligently in the movement. The "probabilistic behavioral models" are similar to the conditional / rule-based models but with various probabilities to invoke the conditions or rules. Meanwhile, the category of the movement model is divided into several branches, in which the movement is influenced by the density of the evacuees, the model user's

Architectural Cue Model in Evacuation Simulation for Underground Space Design

designation, the distance between any two evacuees, the evacuee’s desire indicated by various potential maps, and etc. Notably, the evacuee’s perspective on the environment is also suggested as the classification criteria. In some models called “global perspective model”, the evacuee has a global perspective on the environment and knows everything in it like a user in the environment, which enables him to behave in a global optimistic way. For example, he can always go toward the nearest exit of the whole environment, although he hasn’t seen the exit. In other models called “individual perspective model”, the evacuee has a limited local perspective on the environment, which enables him to behave as a new visitor to the environment. He can only collect information and search the route through his limited perception.

In summary, the above classifications offer us an overview on several important features of the evacuation simulation models. Similarly, these models are studied and classified according to their different methods on the architectural cue modeling, which can contribute to clarify the direction of this research.

2) Classification of Architectural Cue Modeling

Based on the literature studies (Ozel, 1987; Drager, Lovas, & Wiklund, 1992; Santos & Aguirre, 2004; Kuligowski & Peacock, 2005; Kretz & Schreckenberg, 2006; Pan, 2006; Savannah Simulations AG, 2006; Hostikka et al., 2007) focusing on the methods of the architectural cue modeling, the following 36 evacuation simulation models (Appendix A) are classified into two main categories: the global architectural cue supported models and the local architectural cue supported models. Furthermore, the global one is divided into four branches: Designated Route Following, Conditional Shortest-Route Following, Designated Flow Field Following, and Conditional Flow Field Following. The local one is divided into three branches: Preference Level Following, Conditional Nearest-Exit Approaching, and Random Exit Searching. (Table 2.3-1)

Table 2.3-1 Classification according to architectural cue modeling

| Type of the Usage | | Evacuation Simulation Model Supporting the Type |
|------------------------------------|--------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Global Architectural Cue Supported | Designated Route Following | ALLSAFE; ASERI*; EESCAPE; Egress Complex Model; EgressPro; EVACSIM ¹ *; EXIT89*; F.A.S.T; FPETool; GridFlow; Magnetic Model*; MASCM*; PathFinder; PedGo; PEDROUTE*; Simulex |
| | Conditional Shortest-Route Following | ASERI*; BFIRE-2; buildingEXODUS; CRISP3; EGRESS; E-SCAPE; EvacSim ² ; EXIT89*; EXITT; Legion**; MASCM*; Myriad**; SimWALK*; STEPS; Fluid Model; VEGAS** |
| | Designated Flow Field Following | EVACNET4; Magnetic Model*; PEDROUTE*; TIMTEXT; WAYOUT |
| | Conditional Flow Field Following | FDS+Evac |
| Local Architectural Cue Supported | Preference Level Following | BGRAF |
| | Conditional Nearest-Exit Approaching | EVACSIM ¹ *; MASSegress*; SGEM** |
| | Random Exit Searching | MASSegress* |

Notes:

* The model supports different usage types.

** The architectural cue usage is not clearly explained in literatures available.

^{1,2} There are two different models both called “evacsim”.

The above table includes the following models:

| | | | |
|--------------------------------|----------------------------|-----------------------|-----------------|
| <i>ALLSAFE</i> | <i>ASERI</i> | <i>BFIRES-2</i> | <i>BGRAF</i> |
| <i>buildingEXODUS</i> | <i>CRISP3</i> | <i>EESCAPE</i> | <i>EGRESS</i> |
| <i>Egress Complexity Model</i> | <i>EgressPro</i> | <i>E-SCAPE</i> | <i>EVACNET4</i> |
| <i>EVACSIM¹</i> | <i>EvacSim²</i> | <i>EXIT89</i> | <i>EXITT</i> |
| <i>F.A.S.T.</i> | <i>FDS+Evac</i> | <i>Fluid Model</i> | <i>FPETool</i> |
| <i>GridFlow</i> | <i>Legion</i> | <i>Magnetic Model</i> | <i>MASCM</i> |
| <i>MASSegress</i> | <i>Myriad</i> | <i>PathFinder</i> | <i>PedGo</i> |
| <i>PEDROUTE</i> | <i>Simulex</i> | <i>SimWALK</i> | <i>SGEM</i> |
| <i>STEPS</i> | <i>TIMTEX</i> | <i>VEGAS</i> | <i>WAYOUT</i> |

a. Global Architectural Cue Supported Models

In the global architectural cue supported category, the system user explicitly or implicitly offers the global spatial information to the simulated evacuee in some way. Such information is regarded as the global architectural cue, with which the evacuee can calculate and follow the route to the safety. According to the different ways in which the global architectural cue is offered, this category is divided into further four branches.

In the branch of Designated Route Following, a route is explicitly or implicitly designated by the system user using the global architectural cue for the simulated evacuee either as an individual or as a group. There are four approaches to designate the route, which are listed in the following.

1. By inputting an exact route for the evacuee explicitly, such as ASERI, EVACSIM¹, EXIT89, GridFlow, Magnetic Model, MASCM, PedGo
2. By inputting a unique exit to the evacuee explicitly and assuming that he uses the shortest route to approach it implicitly, such as ALLSAFE, EESCAPE, Egress Complexity Model, EgressPro, F.A.S.T.
3. By assuming that the evacuee uses the shortest route to approach a randomly assigned exit implicitly, such as GridFlow
4. By assuming that the evacuee uses the shortest route to the global nearest exit implicitly, such as FPETool, GridFlow, Magnetic Model, MASCM, PathFinder, PEDROUTE, Simulex

In the branch of Conditional Shortest-Route Following, the user assumes that the evacuee searches a global shortest route to a specific exit. An exit is calculated according to a set of variables assigned by the user, such as the availability of the exit in fire, the visibility of the exit in smoke, the familiarity with the exit, the number of the other evacuees around the exit, the number of the lanes of the exit, etc. Once the exit is chosen, the evacuee will approach it in the shortest route.

In the branch of Designated Flow Field Following, the user explicitly or implicitly designates a flow field to the evacuees to guide their movement. The flow field offers the global-optimized egress direction to the evacuee in every spot of the space. There are two approaches to designate the flow field, which are listed in the following.

1. By inputting the exact percentage of every flow of the evacuees in the field, such as TIMTEX, WAYOUT
2. By assuming a rule to generate the flow field, such as EVACNET4, Magnetic Model, PEDROUTE

Architectural Cue Model in Evacuation Simulation for Underground Space Design

In the branch of Conditional Flow Field Following, the user uses both the flow field and the other variables to implicitly decide the evacuees' route. With the other variables influencing the boundary conditions, the dynamic flow field offers the dynamic global-optimized egress direction to the evacuee in every spot of the space.

b. Local Architectural Cue Supported Models

In the local architectural cue supported category, the system user explicitly or implicitly offers the local architectural cue to the simulated evacuee in some way, with which the evacuee can search the route to the safety. According to the different ways in which the local architectural cue is offered, this category is divided into further three branches.

In the branch of Preference Level Following, the user explicitly assigns the value indicating the attractiveness of the local architectural cues to the architectural element. The evacuees perceive these values by their artificial perception mechanism and calculate the route according to the above values from high to low. These values do not correlate to any global information, but are subjectively decided by the user.

In the branch of Conditional Nearest-Exit Approaching, the user implicitly assumes that the evacuees use their limited artificial vision to perceive and approach the nearest available exit around them. Influenced by some other variables, such as the familiarity with the exit, the smoke condition etc., the availability of the perceived exit is dynamic. The evacuees do not make decisions on any global architectural cue but only the perceived local one.

In the branch of Randomly Exit Searching, the user implicitly assumes that the evacuees use their limited artificial vision to search the exit by random exploration. The evacuees do not make decisions on any global architectural cue but only the randomly perceived local architectural cue.

In summary, looking at the classification (Table 2.3-1), it seems that the local architectural cue is not supported so prevalently as the global one. The number of the models in the global category is much higher than the number of the local category. Thirty three of the thirty six evacuation simulation models can make use of the global architectural cues in different extents. While, only four of the thirty six models can make use of the local architectural cues in different extents. (One model can make use of the both kinds of the architectural cues in some extent.) Hence, several questions in the local architectural cue modeling are raised for further discussion in the following section.

3) Problematic Local Architectural Cue

Just as indicated in the classification table, the local architectural cue does not receive as much attention as the global one. In this section, two questions relating to the local architectural cue modeling are raised from the validation reports on evacuation simulation models. With the analysis on the both questions, the problems in local architectural cue modeling are revealed.

a. Two Potential Questions from the Validation Reports

Two potential questions are raised in the validation reports mentioned below. One is which kind of simulation is correct, the global architectural cue based or the local architectural cue based. The

other is whether the user's subjective settings on the local architectural cues are reliable enough for the simulation.

The former question is raised from the fact that the model working with the global architectural cue predicts the evacuee's route differently from the model working with the local architectural cue. In the validation of MASSegress, the predicted evacuee's route differs greatly from the route predicted by Simulex (Pan, 2006). MASSegress works with local architectural cues, in which the evacuees perceive local architectural cues through their limited artificial visions and search the route to the safety according to these cues. In contrast, Simulex works with a global architectural cue, in which the evacuees always take the shortest route to the nearest exit according to the "Distance Map" containing the global information. In fact, to ask which kind of simulation is correct is the same to ask which evacuation strategy is correct. One strategy is to use all the perceived cues to search the route to the safety without a plan or known destination. The other strategy is to use the cognitive map or mental image to plan and follow a route to the safety or a known destination. As it is discussed in Section 2.1.1, both strategies are useful and are adopted in different situations. If the evacuee is familiar with the environment or has some global architectural cue available, he can use the both strategies. However, if he is unfamiliar with the environment and has no global architectural cue available just as in the situation discussed in the research context (Section 2.2), he has to rely on local architectural cues. Thus, it seems that both kinds of simulations are correct and they work for different situations.

The latter question is raised from the fact that there are differences between the simulated data and the observed data caused by the user's subjective settings. In the validation of EVACNET, an unsuspected evacuation with 1014 people in the National Gallery of Victoria is analyzed. The difference between the observed process and the simulated process is noticed. It is explained that two exits seldom used in the normal situation are set as normal exits attracting evacuees by the system user, which leads to the difference directly (Kuligowski & Peacock, 2005). In the validation of EXIT89, a fire drill in a 7-story office building in Newcastle-on-Tyne (UK) is analyzed. The simulated process based on the shortest route assumption provides a shorter evacuation time and much different flow split than the observed process. Similarly, it is explained that a "most direct route possible out of the building" is used by the evacuees rather than the shortest route implicitly set by the model user (Kuligowski & Peacock, 2005). Moreover, in the validation of FDS+Evac, it is reported that with different settings, the model users can get different simulation results as they want. A door will never be used, if it is not set as a "known door" by the user. Vice the versa, set as a "known door", a door must be used, no matter whether it is usable or even perceivable to the evacuees in the reality (Hostikka et al., 2007). With the architectural cues set by the users subjectively, the simulation tool loses its predictive value and acts just as an automatic pen in the user's hand. Meanwhile, the decision based on such model must be very risky when the model is assumed as an objective evaluation tool for human safety. It seems that the user's subjective settings on any architectural cue are not reliable for the simulation.

b. Corresponding Problems

The above two potential questions reveals the corresponding problems in local architectural cue modeling.

The first problem is that local architectural cue modeling has received attention far less than the global one. As discussed in the first question, the local architectural cue is parallel to the global architectural cue. Either of them supports a specific evacuation strategy according to the different

Architectural Cue Model in Evacuation Simulation for Underground Space Design

situation. They should receive similar attention and investigation. However, only a small part of local architectural cues has been touched. As it is discussed in Section 2.1.3, there are at least four information sources offering the local architectural cues. In one of them, only the distance attribute has been modeled to influence the evacuee's route choice in a plausible way, which means that the nearest exit modeling assumption still needs further validation.

The second problem is that the local architectural cue is used in a dangerous way. As revealed in the second question, the user's subjective setting on the local architectural cues will make it very dangerous for the decision makers to rely on the simulation result. Similarly, a potential risk from the subjective settings to the local architectural cues used in BGRAF is mentioned by its builder (Ozel, 1987). With a strong believe that local architectural cues are very important to the route searching behavior in evacuation, he suggests that the evacuees' different preferences on the different local architectural cues should be measured in a more systematic way to improve the accuracy of behavior simulation on route searching.

In general, local architectural cue modeling still needs more attention and investigation. Secondly, the preferences of local architectural cues measured in a systematic way should replace the user's subjective settings.

2.3.3 Summary

In this section, after a brief introduction on evacuation behavior researches, the existing 36 computer-based evacuation simulation models are discussed with a focus on the architectural cue modeling. Finally, it is found that state of the art in local architectural cue modeling still needs more attention and investigation, especially on how to replace the user's subjective settings with systematically measured preferences.

2.4 Measuring Human Preferences Systematically

In the previous section, the problem in local architectural cue modeling reveals that the user's subjective setting on local architectural cues is dangerous and should be replaced with measured human preferences. In this section, several issues of such an investigation are first touched, and some available solutions are discussed. Finally, a combination of the conjoint analysis approach and a virtual reality system, CAVE, is suggested as the potential research method for the investigation.

2.4.1 Environmental Psychology Research Issues

As it is mentioned before, the evacuation behavior research is a subset of the way-finding behavior research, which is also a further subset of Environmental Psychology. Thus, the evacuation behavior research inherits the research issues and methods from the environmental psychology research. In the following, a brief introduction on Environmental Psychology is provided, and the issues of such researches, especially in the evacuation context, are concluded.

1) A Brief Introduction

Environmental psychology is defined as the “psychological study of behavior as it relates to the everyday physical environment” (Lang, 1987). Evans (1982) introduces that the environmentalism and ecological concern of the 1960s helped to generate scholarly interest in the effects of environmental problems on human health. Much of the initial work in this area was done by biological scientists. In the late 1960s and early 1970s, a few behavioral scientists became interested in these effects, focusing on two broad topics: design and user satisfaction, and human responses to the pollution and overpopulation. Later, the researches focus on two key questions: How does variation in the physical environment affect human behavior? How does variation in human behavior affect environmental quality?

Consequently, how the local architectural cues affect the human being's evacuation behavior is a specific form of the first key question. It is expected that the environmental psychology can provide proper theories and research methods to improve the understanding of relationship between evacuees and the built environment, as suggested by Lang (1987).

2) Research Methods in Evacuation Context

It is unethical to make real evacuations for the research (Sime, 1987; Helbing, Farkas, & Vicsek, 2000). However, the evacuation behavior models expect that the simulated evacuees behave similarly as they do in a real evacuation. Thus, all the evacuation behavior researchers have to use “indirect” methods to conduct their researches. Basically, there are two kinds of indirect methods: the real-world survey and the laboratory experiment (Bovy & Stern, 1990).

In the real-world survey, researchers can use post-facto investigations and fire drills to analyze the correlation between the real environment and the evacuation behavior (Ozel, 1987). However, the post-facto investigation can't offer the opportunity to isolate the key causal variables, and only provide limited data for a certain environment, which is not sufficient for a systematic survey. Meanwhile, fire drills can only be used to survey the responses of employees or residents familiar

with the space rather than the visitors in the public space (Arthur & Passini, 1992).

In the laboratory experiment, researchers can use all kinds of presentation forms, such as text descriptions, photos, full-scale or small-scale mocks, to provide a “conceptual” environment to the human beings with a high control on the isolation of the key causal variables (Canter, 1975), which can support a systematic investigation.

According to the proposed systematic investigation on local architectural cue modeling, it is believed that the laboratory experiment method is more suitable rather than the real-world survey method. However, such method raises two questions:

1. What kind of presentation form can offer the most valid conceptual evacuation stimulation?
2. How can the proposed model be validated through indirect evacuation data?

3) Environment Presentation Form

In the following, the first question is going to be answered through exploring the presentation forms in the laboratory experiment. Laboratory experiments share a general method to do a survey on the human beings to analyze the correlation between their perceived information and responses (Regan, 2000). Such a method is mentioned as the experimental psychology method firstly used by Wurzburg, later by Gestalt (Ittelson, 1960). Keys in such a method are: the large number of the participants in the survey (Zimring, 1982) and the complete isolation of the key causal variables (Evans, 1982), which influence the choice of the presentation form greatly. In fact, within an acceptable cost, the suitable presentation form must be able to present the conceptual environment to a larger number of participants coherently and avoid the interferences as many as possible.

Moreover, two features of the physical environment, namely the enormous scale and the variety, mentioned by Canter (1975) are other important factors to influence the choice of the suitable presentation form. With the information offered by the environment, the human being affected by the environment, and their responses collected in the environment, the experiment designer has to consider these two features for the presentation form of his research.

If the research environments are presented in the form of full-scale-mock in the survey, the enormous scale of the physical environment will make it difficult to collect the human beings' responses in a one-by-one means; its variety and profusion will make it difficult to isolate the key causal variables from the other noisy information existing in the reality. Both the scale and variety will make it difficult for the researchers to provide enough full-scale mocks offering specific stimuli to the human beings, which is very important to a systematic survey. For example, Hoogendoorn and Daamen (2005) use three physical environments with specially designed confines as full-scale mocks to study the unidirectional flow with one variable (bottleneck) and three levels (no bottleneck, bottleneck in 1 meter, and bottleneck in 2 meters) through video extraction. Although a very large hall is mentioned to hold the full-scale mock, the research object is still limited to a room scale (14 meters by 12 meters) with the video cam 10 meter high. Obviously, the physical full-scale mocks can only present the research object with a very few variables and levels. With more of them, the research object can not be presented for its enormous scale and variety, which makes it almost impossible to setup enough full-scale mocks or involve enough participants in a statistically acceptable way.

In contrast, if the environments as the research object are presented in other forms, such as text descriptions, photos, videos, small-scaled mocks, in the survey, the enormous three-dimensional

scale of the physical environment will make it questionable if the human beings perceiving the environment in the other forms can behave just as they do in the original one. Consequently, a validation on the research conclusion has to be conducted to answer the question, “To what extent can the conclusion explain the behavior in reality?”

Obviously, according to the proposed systematic investigation on local architectural cue modeling, the full-scale-mock is not suitable for its limited variables and levels. It is necessary to search for other suitable presentation forms for this research.

2.4.2 Development from Paper-and-pencil to Virtual Reality

To find a suitable presentation form for the environment, the development of presentation techniques from paper-and-pencil to virtual reality used in Environmental Psychology in the last half century is studied. After the discussion on these techniques with their features, a suitable presentation form is suggested to support this research.

1) Developing Research Techniques

As introduced by Bovy and Stern (1990), the techniques used in the environmental psychology, especially in the way-finding behavior research, to indirectly present the conceptual environment to the human being can be classified into three categories: the paper-and-pencil technique, the visual aid technique, and the simulator technique.

a. Paper-and-pencil Technique

Bovy and Stern (1990) define the paper-and-pencil technique as an experiment in which individuals respond to hypothetical situations only described to them by text. For example, Stern, Tzelgov, and Henik (1983) use it to describe the situation in different choices to survey the effect of driving efforts within the context of the orthodox route choice determinants of time, speed, and length. Moreover, Kroes and Sheldon (Bovy & Stern, 1990) extend the technique to a kind of choice option cards.

The paper-and-pencil technique can keep the environment representation extremely “conceptual”. It forces the human being to imagine the environment only according to what is described and avoid any other interference. However, its sequential perception process breaks the simultaneous spatial perception into a chronological way, and its dependence on the language-to-form imagination has potential problems from the variety of the individual knowledge.

b. Visual Aid Technique

With the above problems, Environmental Psychology upgrades the technique with the visual aids, such as maps, slide, video films, etc. These visual aids provide the represented environment to the human beings with all the aspects simultaneously perceivable and independently from the individual language-to-form imagination. For example, Bovy and Bradley (1985) use it to study the route choice behavior of bicyclists in urban areas. Stern and Leiser (1988) use such method to study the residents’ preferences on the different routes connecting the same origin and destination in Beer

Sheva.

Besides these researches, the researchers want to know to what extent the “conceptual” environment represented by the visual aids can invoke the human being’s response as in a real environment. Due to experiments Gombrich (Rogers, 1995) concludes that an observer's judgments about the depicted scene in photos match those made when the real thing is presented. Canter and Wools (Canter, 1975) compare the evaluations of the room interiors between the drawing-based and the on-site based experiment. Aking and Kuller, Shafer and Richards (Canter, 1975) compare the judgments between the film-based and the on-site based experiment. Based on these validations, Canter (1975) concludes that “close similarities are found between the judgments in the various media”. Notably, a difference in the movement speeds is revealed between different environmental representations. Stamps (1990) concludes that there are strong relationships between preferences obtained in the environment and preferences obtained through the photos. Ulrich et al. (1991) shows that viewing photos has physiological effects, which is similar to the experience of natural environments. Bateson and Hui (1992) report the slides of a railway ticket office invokes the same psychological and behavioral phenomena (related to consumer density) as the actual setting does. Lombard (1995) states that there are some compelling empirical evidences that media users react to televised presentations in the same ways that they react to nonmediated events, objects, and people despite the fact that mediated presentations provide a limited reproduction of the nonmediated experience.

However, the visual aid technique has its limitation. The human beings have to receive the stimulation of the represented environment in a passive way, which is obviously unrealistic in the real behavior.

c. Simulator Technique

To overcome the limitation of the passive perception, the researchers develop the simulator technique. The paper-and-pencil technique offers a high level abstraction, which forces the human beings to imagine not only the forms of the environment but also how he interacts with the environment. With more formal details and less abstraction in the visual aid technique, the human beings do not need to imagine the forms of the environment, while it still needs the imagination of the human-environment interaction. With the least abstraction, the simulator technique offers the opportunity of the human-environment interaction, with which the human beings not only perceive an environment but also experience the changes of the environment caused by their behaviors just as in the reality. Consequently, the simulator has the ability to elicit from the human being the same response that he will make in a real situation (Bovy & Stern, 1990). For example, the fixed-base vehicle simulators (TNO 1978; Scott 1985) are used to study the navigation and driving behavior.

With the rapid development in the computer graphics, there is a trend to build the simulators with the virtual reality technologies (Bailenson et al., 2001), which provides a possibility for the simulator to hold various environments from room to city in a convenient way.

2) Virtual Reality (VR) Based Simulator Technique

Webster’s Dictionary gives the definition of virtual as “being in essence or effect, but not in fact”, and the definition of reality as “a real event, entity, or state of affairs”, from which Spring (1991) deduces the definition of “virtual reality” as “a fact or real event that is such in essence, but not in fact”. Furthermore, he regards it as a form of interactive interface characterized by an

environmental simulation controlled only in part by human beings. Thus, the VR-based simulator technique is defined as the means with a computer-based interactive interface between the human beings and a represented environment.

a. Two Expectations on VR-based Simulator Technique

It seems that some philosophers regard all worlds, such as the world of story-telling, film-making, science, religion, art and even the perceived world, as contingent symbolic constructs (Heim, 1991), which means everything in the world is a kind of virtual reality based simulator. It is not necessary to involve into such a discussion, and only the VR-based simulator technique in the context of computer-based interactive interface is discussed. However, there are still two opposite expectations on the development of the VR-based simulator technique somehow relating to the philosophers discussion.

Some researchers try to improve the represented environment as realistic as possible. They believe that as a display better approximates the environment it represents, an observer's responses to stimuli within the display will tend to approximate those that he would exhibit in response to the environment itself (IJsselsteijn et al., 2000; Freeman et al., 2000). Furthermore, Loomis, Blascovich, and Beall (1999) argue that "the ultimate representational system would allow the observer to interact 'naturally' with objects and other individuals within a simulated environment or 'world,' an experience indistinguishable from 'normal reality'".

In contrast, other researchers try to keep the represented environment at a proper abstract level. They believe that a virtual world needs to be not-quite-real, otherwise it will lessen the pull on imagination. Something-less-than real evokes human power of imagination and visualization (Heim, 1991).

In fact, the two expectations reveal the great flexibility of such technique. It can both represent the environment in a very realistic way to include any key causal variables, and represent the environment in an abstract way to exclude any interference, which always coexist with the key causal variables in reality. With such flexibility, the technique has many advantages.

b. Advantages

There are several researches concluding the advantages of the VR-based simulator technique in environmental psychology researches (Dijkstra & Timmermans, 1997; Loomis, Blascovich, & Beall, 1999; Rose & Foreman, 1999; Kuhlen, Kraiss, & Steffan, 2000; Tan & de Vries, 2000; Bell et al., 2001; Tan, 2003). Generally they mention the following five issues.

First, it is the only way to experience navigation in space. The VR-based simulator technique offers the real-time interaction between human and the computer generated scenario, which means that people can navigate in the virtual environment as in the real one.

Second, it is easy to control the stimulations for the experiment designer. With the support of computer graphics, the designer can decide the level of abstraction for the visual stimulation and what interference should be excluded. Meanwhile, the scenario which is very difficult to built or even not existing in the reality can be generated by computer easily. Notably, the dangerous circumstances, such as evacuation scenarios, can be represented without any risk. Furthermore, with the support of computer multimedia, the designer can use other kinds of stimulations, such as the

Architectural Cue Model in Evacuation Simulation for Underground Space Design

sound, to enhance the stimulation. Finally, with the support of computer programming, the designer can always provide the same stimulation to every experiment participant.

Third, it is easy to control time or sequences. With the support of computer programming, the experiment designer can decide the time period and sequence of the experiment process easily. Some tricks, such as time compaction and rapid switch between different scenarios, are available and sometimes very useful for the experiment in the large scale environment.

Fourth, there is less interference from other persons. Navigating in the VR-based simulator, the experiment participant interacts with the computer interface alone, which makes him behave more naturally than he behaves with some other experiment staffs beside.

Fifth, it is easy to record complex spatial behavior. With the support of the computer programming, it is very easy and accurate to record all the participants' inputs as a representation of their spatial behavior.

In summary, the VR-based simulator technique is the only one enables human beings to experience the space. It offers great flexibility on the stimulation control not only on the context but also on the sequence. Moreover, it provides the accuracy and convenience to the data collecting. However, any technique can't be perfect. Its limitations are discussed in the following.

c. Limitations

There are also two main limitations mentioned in Tan's research (2003), in which she compares the way-finding performances in the two experiments supported by VR-based simulator technique and paper-and-pencil technique. She argues that the VR-based simulator technique provides a worse sense on time duration and worse sense on spatial orientation.

However, it is believed that her argument on spatial orientation is questionable. She uses a global map in the paper-and-pencil experiment, while she uses the local view based VR platform for the other experiment. In fact, her comparison is between way-finding performances based on the global cue and the local cue.

In general, it is suggested that with the same cues, the VR-based simulator technique is the state of the art, according to the development of the environmental psychology research techniques.

d. Validity

Like other techniques, the VR-based simulator technique needs to be validated to measure to what extent the virtual environmental stimulation can invoke the human being's response as in a real environment.

Although the perception space is regarded a curved space with Riemannian curvatures, it is argued that the curvature degree of the physical space is so small on a local level that it can be approximately treated as Euclidean space (Cutting & Vishton, 1995). With this argument, the space through the human vision matches the three-dimensional space in computer graphics, and the VR-based simulator technique has its foundation in the environmental psychology researches.

It seems that the positive conclusions and negative conclusions coexist in the validation. Murray et

al. (2000) reports a continuous relationship between real and virtual worlds based on an analysis of the interaction of people with a virtual city. O'Malley and Goldfarb (2002) report that the haptic size identification and discrimination performance are quite comparable in real and simulated environments. However, Witmer et al. (1996) states that the navigation within virtual environments is not as simple as in the real world and can lead to a higher tendency of a user becoming lost. Nash et al. (2000) reports a considerable knowledge on basic task performance in virtual environments and differences with that in real environments. Similarly, the egocentric distance estimations in virtual environments are reported quite poor (Ellis & Menges, 1997; Witmer & Kline, 1998; Hu et al., 2000; Willemsen & Gooch, 2002)

It is believed that the conflicting validation conclusions come from the nature of VR as sets of techniques. VR is a general name for a set of different techniques used in the computer-based interaction interface, which means every individual technique has its advantages and limitations. It is unfair to validate one technique out of its limitations and use its result to stand for all the others. For example, all of the above researches are done with a special kind of VR system namely Head Mounted Display (HMD) (de Kort et al., 2003), which has a strongly limited view field. With such a narrow view field, human being has to turn his head frequently to observe the surrounding environment, which probably causes the disorientation in the virtual space mentioned by Witmer et al. Furthermore, the context of the VR-based representation will influence the human beings' performance. The improvement of VR technology itself will influence it, too.

With the understanding of the diversity and potentiality of VR technologies, this research holds a positive view to its validity. According to that the capability of VR can offer any kinds of visual aids and have an extra feature of real-time interaction, I agree with Wilson (1999) on that the validity of the VR-based simulator is better than the visual aided techniques, which has already been positively validated by a relatively rich set of researches (Canter, 1975; Stamps, 1990; Ulrich et al., 1991; Bateson & Hui, 1992; Lombard, 1995; Rogers, 1995).

Although there are still debates on the validity of VR technology applied in environmental psychology researches, there are more and more researchers taking it as their choice. In the following, some researches supported by VR-based simulator technique are introduced.

e. Researches

The success of VR-based simulator might begin with in the military training. With its ability to represent the environment in a realistic and interactive way, it is so trusted that before the soldiers go to fight somewhere unvisited, the virtual site is used to train them (Banks & Stytz, 2003; Stytz & Banks, 2003a; Stytz & Banks, 2003b).

Meanwhile, the VR-based simulator techniques are use in environmental psychology researches (de Kort et al., 2003). Kuhlen, Kraiss, and Steffan (2000) use it for the motion studies. Bailenson et al. (2001) uses it for the equilibrium theory's specification of an inverse relationship between mutual gaze, a nonverbal cue signaling intimacy, and interpersonal distance. Pertaub, Slater, and Barker (2002) use it to study the speaker's behavior in front of different audiences.

The VR-based simulator techniques offer the opportunity to implement a carefully designed statistic experiment with the multitudinous participants behaving and observed in the virtual environments. Dijkstra and Timmermans (1997) build a system for interactive conjoint-based analysis in virtual reality of user satisfaction and complex decision making. Tan and de Vries (2000) use the VR

technique to measure the human behavior of activity scheduling. Dalton (2001) uses it to measure the angular preferences of pedestrian's turning behavior and reveals the potential minimizing-angle rule. Werner and Schindler (2004) use it to measure the correlation between the reference structural frames and the way-finding performance, and he concludes that with the integration of spatial knowledge gained through a number of local views, exploring a building is more difficult when the local reference frames are misaligned.

With the advantage to represent the environment in disaster and avoid ethical problems, the VR techniques are used in evacuation behavior researches. Johnson and Feinberg (1997) use it to quantitatively survey the social behavior of the evacuees facing with different exit instructions and the different number of available exits. Shih, Lin, and Yang (2000) use it to measure the evacuation time against the traditional calculation method for evacuation planning in Japan. Murakami et al. (2002) uses the distributed VR platforms to measure the leading and following behavior in emergency, which form the sub model of the evacuation simulation model MASCM

In summary, the VR-based simulator technique provides the state-of-the-art presentation form of the environment to the researchers. Although the question, like "do we behave in VR similarly as we do in reality", is always heard, it is believed that with the research techniques developed from paper-and-pencil to simulator, the VR-based simulator inherits the validity of the other traditional techniques, and even goes beyond them with the possibility of the interaction and the flexibility on stimulation control. This is the answer to the previous question, "What kind of presentation form can offer the most valid conceptual evacuation stimulation?" However, as the human being's experience and performance in VR is likely influenced by various characteristics of the simulation, cues, and interaction devices (Wanger, Ferwerda, & Greenberg, 1992; Cutting & Vishton, 1995; Witmer & Kline, 1998; IJsselsteijn et al., 2000; Nash et al., 2000; IJsselsteijn et al., 2001; Janzen et al., 2001; Riecke, Van Veen, & Bulthof, 2002), a proper VR technique from the booming technologies has to be chosen according to the features of this research (Section 2.2).

2.4.3 Measurement of Preference in Virtual Reality

As argued in the above section, a proper VR-based research method is suggested in this section. As Utility Maximizing Model is selected as the proper framework of decision making on local architectural cues in the research context (Section 2.2.3), the Conjoint Analysis (CA) approach supported by a VR-based simulator technique is suggested as the potential method for this research. In the following, a brief introduction on the conjoint analysis approach is first given. Next, the reasons why the VR-based CA method is used are discussed. Finally, a special VR technique, the CAVE system, is introduced and suggested as the technique for the research context.

1) Conjoint Analysis (CA) Approach

Conjoint analysis is a generic term coined by Green and Srinivasan referring to a number of paradigms in psychology, economics and marketing that are concerned with the quantitative description of consumer preferences or value tradeoffs (Timmermans, 1984; Dijkstra & Timmermans, 1997). It sometimes also referred to the stated preference modeling, which involves the use of designed hypothetical choice profiles to measure individuals' preferences for choices of those new profiles (Oppewal, 1995). Wittink and Cattin (1989) explain that the marketing analyzer can use Conjoint Analysis approach to estimate a model from responses that are collected in experimentally controlled hypothetical situations. Descriptions of hypothetical alternatives are

presented to the participants who are asked either to rate their preference for these alternatives (usually profiles of attributes) or to choose from sets of alternatives. With the attributes mutually independent in the profiles and because the hypothetical alternatives not restricted to participants' current domains of experience, this approach allows one to obtain estimates that are efficient and that are not confounded with the characteristics of the current real-world choice situation. Numerous consumer studies have applied this technique in a large variety of research areas.

Hair et al. (1995) concludes that Conjoint Analysis serves two major objectives: One is to determine the contributions of predictor variables (attribute levels) and their respective values (utilities) to user preference. The other is to estimate a valid model to predict the user preference of any combination of the attributes. Thus, it is a method that can be used to estimate Utility Maximizing Model. Similar as many other researches on the spatial choice (Timmermans & Golledge, 1990; Garling, 1999), this research can use it to estimate the evacuees' preferences on the local architectural cues according to their spatial attributes.

2) Advantages of VR-based CA

As Vriens (1995) and Dijkstra and Timmermans (1997) suggest, with the advantages from the other techniques (Section 2.4.2), the VR-based simulator technique is more suitable to present the profiles of spatial alternatives to the participants in a CA-based research.

Meanwhile, the Conjoint Analysis approach also offers two beneficial features to incorporate the VR-based experiment on the spatial alternatives. One is that the experiment designer can replace a large number of profiles (scenarios) with all the attribute combinations for the participants' evaluation with a much smaller number of profiles (scenarios) supported by the fractional factorial design techniques in CA (Montgomery, 1991), which can also work perfectly with a scenario generation program in VR and save a lot of efforts on the scenario preparation. The other is that the prediction ability of CA (Oppewal & Timmermans, 1999) matches the nature of VR perfectly. The experiment designer can ask the participants to evaluate the profiles (scenarios) with the attribute combination not existing in reality at all. Such unseen profiles (scenarios) can be easily presented in VR system.

Some researches clearly demonstrate the above advantages of VR-based CA experiment on spatial alternatives. For example, Dijkstra and Timmermans (1997) develop ICARUS system for VR-based Conjoint Analysis research. They conduct several researches on the spatial alternatives, such as measuring the user preference of the signage for way-finding. Orzechowski (2004) develops MuseV3 system to measure the user satisfaction in virtual environments, in which the participants' modifications on the design are used to estimate the design preference.

3) Potential VR Experiment Platform

As it is discussed in the previous section, there are dozens of computer-based techniques under the concept of VR. In this section, it is suggested that the CAVE system is the suitable technique among them according to the human vision specifications. Meanwhile, several visual cues are introduced, which can help us to improve the spatial perception of the local architectural cues in the CAVE system.

a. Specifications of Human Vision

Human vision is the medium between the participants and the represented environment in the VR system. Thus, it needs to be specified before any VR technique is chosen.

View Field

It is reported that the monocular view field is approximately 60 degree up and 75 degree down; 100 degree to one side and 60 degree to the other. The binocular view field is approximately 120 degree wide, 60 degree on either side of the vertical midline (Henson, 1993). In the vertical view field, about 40 degree is above the eye level, and about 20 degree below the eye level (Ashihara, 1970).

Angular Judgment

It is reported that human beings can judge the relative angle accurately (Hershenson, 1999).

Depth Judgment

As an important way to judge depth (distance along the sight line), the binocular stereoscopic vision is reported to work at a close distance, no more than 4.9 meters, to the eye (Hall, 1966). Beyond this distance, other visual cues are used to estimate the depth.

Distance Judgment

It is reported that the reliable distance judgment work within 30 meters. While, some other researchers report that it works within the distance between 30 and 100 meters (Gilinsky, 1989; Hershenson, 1999). Thus, it is suggested that the perceived distance corresponds fairly well to real distance up to about 100 meters. Meanwhile, the static and dynamic distance judgments are both reported reliable (Cutting & Vishton, 1995).

With the above capabilities, human beings can perceive the space in a real environment. Accordingly, they serve as the criteria for choosing the suitable VR technique for the environmental experiment.

b. CAVE as A Suitable VR System

According to the above specifications of human vision, it is proposed that the CAVE system is a suitable choice for the experiment in the research context. The CAVE system, originally created by the Electronic Visualization Laboratory of the University of Illinois at Chicago, is a cube-shaped space with stereo projections on three walls and on the floor, which are adjusted to the viewpoint of one of the users inside (Friedman, 2005). Later, for different purposes, various CAVE systems are built, which share the features: the capability to cover the whole human view field and to provide the full scale virtual object in the view.

These both features are very important to this research and distinguish it from the other VR techniques. As mentioned before, if the view field is not covered by the VR system, the participant has to turn his head frequently, which will bring the interference to the virtual evacuation behavior from the disorientation in the space and the asynchronous perception of the cues. On the other hand, it is reported that the scale of the image influences the spatial perception greatly (Rogers, 1995). If the evacuee can't perceive the spatial object, the local architectural cue, correctly with its geometric attributes, the measurement on the preference of it can't be correct correspondingly.

Thus, it is proposed that the CAVE system is the suitable choice for this research.

c. Visual Cues for Spatial Perception

Besides the basic vision capabilities, human beings can use some visual cues to deduce the spatial relationships of the objects in the environment. These cues offer a rich set of strategies for us to improve the spatial perception in a CAVE system. Before the psychologists study these visual cues, the ancient artists have already used them in their paintings for thousands of years. A list of the eleven visual cues is compiled from the literatures (Ittelson, 1960; Porter, 1979; Lam, 1992; Cutting & Vishton, 1995; Hall, 1966; Hershenson, 1999; Regan, 2000) as the following.

Size:

The discrimination of distances is dependent on the size of the retinal image provided by an object.

Overlay:

The cue of interposition occurs when an overlapping object is said to be nearer than an overlapped object.

Linear perspective:

A constant distance between points subtends a smaller and smaller angle at the eye as the points recede from the participant.

Color:

The warm color always seems closer than the cold color.

Aerial perspective:

When surface details of an object do not provide conditions for requisite visual contrasts, a participant reports that the object seems far off.

Movement parallax:

When a participant's eyes move with respect to the environment, or when the environment moves with respect to a participant's eyes, a differential angular velocity exists between the line of sight to a fixated object and the line of sight to any other object in the visual field.

Light and shade:

Various combinations of shadow and highlight are reported as objects having various dimensions and lying at different distances.

Accommodation:

Differential aspects of "blur circles" in a retinal image may elicit spatial discrimination.

Convergence:

When an object is at a great distance, lines of fixation to the object are parallel. When the object is near at hand, the participant's eyes are turned in a coordinated manner so that the lines of fixation converge on the object. Convergence may serve as a cue for depth responses.

Height in visual field:

In the case of flat surfaces lying below the level of the eye, the more remote parts appear higher, and the object with the same elevation of the eye never changes its height in vision when the distance changes.

Motion perspective:

In walking along, the objects that are at rest by the wayside stay behind us; that is they appear to glide past us in our field of view in the opposite direction to that in which we are advancing. More distant objects do the same, only more slowly, while very remote bodies like the stars maintain their permanent positions in the field of view.

Any of the above visual cues can offer the spatial relationships between the objects. With them, the virtual scenarios presented in the CAVE system can be designed for this research.

2.4.4 Summary

In this section, with an analysis of the issues of the environmental psychology researches and the evacuation behavior context, it is suggested that the VR-based simulator technique can provide a suitable presentation form of the environment for the indirect laboratory experiment. Furthermore, a special VR system, CAVE, is selected to combine with the Conjoint Analysis approach to measure the evacuees' preferences on the local architectural cues systematically. Finally, some visual cues that can improve the spatial perception are introduced for the visual stimulation design in CAVE for the following research.

2.5 Summary of the Chapter

In this chapter, through the literature studies the first research question (How does the space design of complex public underground environment influence evacuee's route searching process?) is answered.

Within the context of the complex public underground space design, this research sets out from an architectural view to conclude that according to the literature studies, the evacuees search the architectural cues (in this case only the local ones) in their view and choose the cue with the highest possibility leading to the safety by their estimations, just as Utility Maximizing Model works. Then they move to the direction hinted by the chosen cue. Besides, the architectural cue modeling in the existing 36 evacuation simulation models is also studied. It is argued that the local architectural cue has not received enough attention and still needs a systematic measurement on evacuees' preferences. Thus, the issues of such an investigation are discussed and the CAVE-based Conjoint Analysis approach is suggested as the potential research method.

However, through the literature studies, several further questions are raised, through which the second research question (How can such a process based on local architectural cue choice be modeled in an architect-oriented evaluation tool?) can be answered. These further questions are:

1. From what architectural element can the evacuees perceive the local architectural cues in the context of complex public underground space designs? (Section 2.1.2)
2. What is the knowledge about the cognition rules and the related events of these local architectural cues? (Section 2.1.2)
3. How can the knowledge be used in the Cue-Choice model? (Section 2.1.2)
4. How can the qualitative conclusions on the four information sources offering the local architectural cues be transferred to the quantitative variables driving the model? (Section 2.2.1)
5. How can the proposed model be validated through indirect evacuation data? (Section 2.4.1)

3 Development of the Computational Model

In this chapter, the second research question (*How can such a process based on local architectural cue choice be modeled in an architect-oriented evaluation tool?*) is answered, from which two aims of the modeling research are set in the very beginning. One is to build a computational model for a defined scenario and application context. The other is to build this model to support an architect-oriented criterion for the evacuation evaluation on space designs.

As it is mentioned in the end of Chapter 2, there are still several questions to be answered to describe how the evacuee searches his route to the safety in the complex public underground space designs in a computational model. Thus, the computational model is built through answering these questions correspondingly. First, an overview is created on how the local architectural cues are recognized and used by people in the evacuation of the complex public underground spaces. Second, a CAVE system is setup to observe the evacuation behavior to elicit the cognition rules and related events of the local architectural cues. Third, a hypothetic model framework is hypothesized from the literature studies and the conclusions derived from the observation experiment. Fourth, a set of CAVE-based conjoint analysis experiments is designed and implemented to transit the qualitative knowledge about the four information sources offering the local architectural cues to a set of variables driving the evacuation behavior quantitatively.

Finally, with all the components of the computational model prepared, the computer-based prototype named SpaceSensor is built. Through two demonstrations with SpaceSensor, it is shown how the evacuee searches his route in the complex public underground space designs and how the architect uses this model to evaluate his design by an architect-oriented criterion. In other words, the computer-based prototype SpaceSensor is the answer to the second research question.

3.1 Aims

Two aims are set for the modeling research. First, it must be explained how the evacuee searches his route to the safety in the complex public underground space designs in a computational model. Next, this computational model must provide an architect-oriented criterion to evaluate the space designs.

3.1.1 Process Explained in a Computational Model

To explain the process in a computational model, a specific application context is defined for the model and an evacuation scenario is defined for the process.

1) Application Context

The model is built for a specific application context, in which the architect wants to predict how the evacuee searches his route to the safety in complex public underground space design. Only the space design is needed for such a prediction, which contains the information of the space organization and the configuration of the abstract three-dimensional geometric features of all the architectural elements for the circulation system.

Thus, the model can be used to evaluate the space design in the initial design stage to check whether the evacuees use the routes as the architect planned, and it can also be used to evaluate the space design as a part of the integrated design in any later design stage to check whether it works coherently with the other cues, such as signs.

2) Evacuation Scenario

The model is built to explain the process in a specific scenario. According to the discussion of the specific evacuation behavior in complex public underground space designs in Chapter 2, the scenario is defined as the following:

When: The model is to simulate the behavior during “movement phase” in a “Simultaneous Evacuation” process.

Where: It is to simulate the behavior inside “Exit Accesses”, which is the linkage between the Occupied Rooms and the Exits.

Who: It is to simulate the behavior of the visitors unfamiliar with the environment (without any mental image or cognitive map about the environment in the brain).

What: It is to simulate the behavior of the evacuee searching the route to the safety, which works as the “Cue-Choice” model with three phases:

1. The evacuee searches all the local architectural cues perceived from the environment.
2. The evacuee chooses one local architectural cue in a decision making process.
3. The evacuee evacuates to the direction hinted by the chosen local architectural cue.

Cues: It is to simulate the behavior influenced by the local architectural cues. They distinguish

themselves by the abstract three-dimensional geometric features, which reflect the four kinds of information: the type of the architectural element in the circulation system, the distance from the architectural elements to the individual, the scale of the architectural element, and the angular positions of the architectural elements in the individual's view.

Decision Making: It is to simulate the behavior under the rational decision making. It uses Utility Maximizing Model, in which the evacuee estimates the leading-to-safety utilities of several perceived local architectural cues according to their three-dimensional geometric features, and he chooses the cue with the highest utility through a series of paired comparisons to use its hint egress direction as the goal of next movement.

3.1.2 Design Evaluation with an Architect-oriented Criterion

A new criterion, Local Evacuation Efficiency Index (LEEI), is defined for the architect's evaluation on space design. As mentioned in the previous application context, during space design architects have more interest in whether the evacuee moves along the route as they plan rather than in how many seconds the evacuee finishes the evacuation. Thus, the relative evacuation efficiency is a better indicator than the absolute RSET during the space design.

The ratio of Shortest-Distance-To-Safety (SDTS) to Predicted-Distance-To-Safety (PDTS) is suggested as the relative evacuation efficiency indicator for a certain evacuation starting point, which is called Local Evacuation Efficiency Index (Eq.1). With a given space design, a unique SDTS can be calculated through some algorithms (e.g. Dijkstra algorithm or A-star algorithm), and PDTS can be predicted by the proposed model. The value of LEEI has a range from zero to one. When LEEI is close to one, the architect can ensure that the architectural elements are designed well enough to offer the right local architectural cues inducing the evacuees to choose the most efficient route to the safety. In contrast, when LEEI is close to zero, the evacuees are misled by some architectural cues to an inefficient route. Consequently, a detailed analysis on the space design along the route is needed. In such an analysis the problems in the space design can be revealed according to the simulation process reported by the proposed model.

$$LEEI = \frac{SDTS}{PDTS} \quad (1)$$

3.1.3 Summary

According to the defined application context and the evacuation scenario, a computational model is built to explain how the evacuee searches his route to safety in a complex public underground space design. Moreover, this model must support the LEEI criterion for the architect to evaluate his space design.

However, there are still several questions raised in the end of Chapter 2 that need to be answered, to explain the route searching process in a computational model. Thus, in the following the computational model is built through answering these questions one by one.

3.2 Survey of Local Architectural Cues

To answer the first question in the end of Chapter 2, questionnaires are used to survey from what architectural element the evacuees can perceive the local architectural cues in the context of complex public underground space designs (Sun & de Vries, 2006). From these cues, the most important local architectural cues are selected for the following research.

3.2.1 Overview

During February 21st - 28th 2006, 102 students (47 males and 55 females with the average age at 21, SD=1.1) in College of Architecture and Urban Planning, Tongji University, Shanghai, China participated in the questionnaire survey (Appendix B).

3.2.2 Procedure

The questionnaire first asks the participant to imagine an evacuation scenario: He is walking in a complex public underground space. Suddenly the broadcast asks him to evacuate immediately. At the same time he can see the elevators and the escalators stop working. There are 12 types of the architectural elements in his view field, which offer the different hints of the evacuation directions to him. Afterwards, the questionnaire asks the participant to use his intuition to sort these elements by his estimation on their probabilities leading to the safety. If he feels an element doesn't offer any hint, he can cross it and leave it out of the list. If he has some additional type of element offering any hint, he can add it to the list with some explanation. Any further description on how to use the element or why it has a high or low probability is welcomed.

Receiving the questionnaire from the participant, the list is checked and the participant is interviewed on how he would like to deal with the architectural element in an evacuation and why some architectural elements receive very high or low probability when they are out of my expectation.

After collecting all the questionnaires, the 12 sequences of the architectural elements in the list are mapped into Level 1 to 12, in which the top architectural element indicating the highest probability leading to the safety is mapped to Level 1. The number of the votes is counted for a certain type of architectural element in every level. According to the median level of every architectural element, they are sorted (Table 3.2-1).

Table 3.2-1 Ranked local architectural cues in underground spaces

| Architectural Element | Median Level | Votes in every ranking level | | | | | | | | | | | | Total |
|------------------------|--------------|------------------------------|----|----|----|----|----|----|----|----|----|----|----|-------|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | |
| Vertical Outdoor Light | 1 | 58 | 18 | 9 | 5 | 5 | 1 | 2 | 0 | 3 | 1 | 0 | 0 | 102 |
| Up Stair | 3 | 13 | 31 | 20 | 13 | 7 | 8 | 2 | 4 | 2 | 1 | 1 | 0 | 102 |
| Exit | 3 | 20 | 18 | 17 | 13 | 7 | 2 | 3 | 4 | 4 | 5 | 5 | 4 | 102 |
| Doorway Entrance | 6 | 3 | 4 | 5 | 10 | 26 | 16 | 10 | 9 | 7 | 8 | 2 | 2 | 102 |
| Raised Ceiling | 6 | 1 | 6 | 12 | 14 | 13 | 13 | 12 | 9 | 7 | 6 | 9 | 0 | 102 |
| Columns | 6 | 3 | 7 | 9 | 13 | 11 | 13 | 9 | 13 | 11 | 6 | 6 | 1 | 102 |
| Lighted Ceiling | 7 | 2 | 5 | 11 | 12 | 5 | 15 | 18 | 6 | 15 | 5 | 2 | 6 | 102 |
| Escalator | 7 | 2 | 5 | 11 | 8 | 10 | 11 | 16 | 10 | 13 | 6 | 9 | 1 | 102 |
| Handrail | 8 | 0 | 0 | 1 | 6 | 8 | 13 | 11 | 24 | 12 | 10 | 8 | 9 | 102 |
| Sight Lift | 10 | 0 | 6 | 4 | 3 | 4 | 2 | 8 | 8 | 7 | 24 | 25 | 11 | 102 |
| Down Stair | 10 | 0 | 0 | 3 | 4 | 4 | 5 | 3 | 10 | 15 | 13 | 7 | 38 | 102 |
| Lift | 11 | 0 | 2 | 0 | 1 | 2 | 3 | 8 | 5 | 6 | 17 | 28 | 30 | 102 |




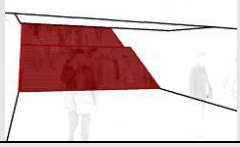

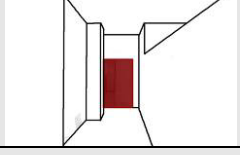

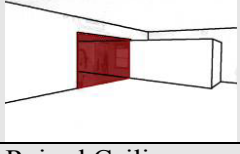

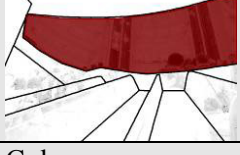

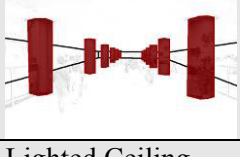



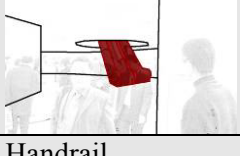

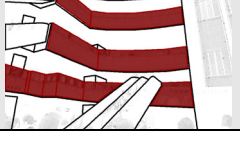
3.2.3 Conclusions


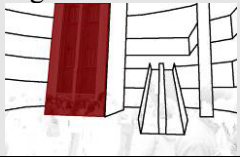

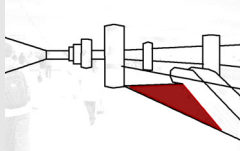

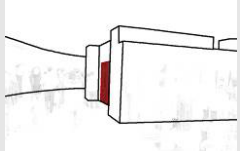
From the interviews and the above table (Table 3.2-1), the following issues are concluded.

- 1) The twelve alternatives all prove capable to offer the hint of evacuation direction to a different extent, which is regarded as the local architectural cue in this research. Besides them, there is no additional architectural element offering such a hint revealed.
- 2) Exit is not regarded always safe as the architect plans. Almost all of the participants mention their hesitation in voting between Exit and Up Stair. They explain that the tons of reports on the blocked exits causing death in fire in China make them hesitate to use Exit. In contrast, Up Stair can get them closer to the safety directly.
- 3) The attractiveness of the elements is different, which reflect the participants' considerations on them (Table. 3.2-2). In the underground evacuation, the outdoor space and ground level are considered as the safety. Vertical Outdoor Light undoubtedly receives the highest probability leading to the safety directly. Next two elements with strong attractiveness are Up Stair and Exit. Several elements with medium attractiveness are Doorway Entrance, Raised Ceiling, Columns, Lighted Ceiling and Escalator. The weakest elements are Handrail, Sight Lift, Down Stairs, and Lift.

Architectural Cue Model in Evacuation Simulation for Underground Space Design

Table 3.2-2 Evacuee’s consideration on the architectural elements

| Real Scene | Architectural Element | Evacuee’s Consideration |
|-------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------|
|  | Vertical Outdoor Light  | It is believed to lead the evacuee to the outdoor space on the ground. |
|  | Up Stair  | It is believed to bring the evacuee closer to the ground level. |
|  | Exit  | It is believed to lead the evacuee to a fire resisting room containing stair to the ground level. |
|  | Doorway Entrance  | It is probable that the evacuee can find exits or stairs hidden behind the wall of the Doorway entrance. |
|  | Raised Ceiling  | It is probable that the evacuee can find a hall containing stairs or exits under Raised Ceiling. |
|  | Columns  | It is probable that the evacuee can find exits or stairs along the axis of Columns, which usually matches the circulation system axis. |
|  | Lighted Ceiling  | It is possible that the evacuee can find exits or stairs under Lighted Ceiling, if the light is natural from outdoor space. |
|  | Escalator  | It is possible that the evacuee can use a stopped Escalator as Up Stair with big steps. |
|  | Handrail  | It is possible that the evacuee can find exits or stairs along Handrail, which usually parallels one of the flows in the circulation system. |

| | | |
|-----------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|  | <p>Sight Lift</p>  | <p>It might be designed with exits or stairs around.</p> |
|  | <p>Down Stair</p>  | <p>It might be a chance to leave the current floor and look for exits or stairs on another floor. However, a huge hesitation to use it in the underground is mentioned.</p> |
|  | <p>Lift</p>  | <p>It might be designed with exits or stairs around.</p> |

4) Up Stair, Exit, and Doorway Entrance are selected. As a Vertical Outdoor Light always follows an Exit or an Up Stair to the ground floor, it is combined into these two kinds of elements. According to the Egress Design and Review Checklist (Tubbs & Meancham, 2007) summarized from the International Building Code (International Code Council, 2006) and the Life Safety Code (National Fire Protection Association, 2006), only the following top three architectural elements: Up Stair, Exit, and Doorway Entrance, in the sorted list (Table 3.2-2) are mentioned relating to the designs of the egress path, the egress width, the exit distribution, the exit width, the stair distribution and the stair width. Meanwhile, the rest architectural elements in the sorted list are not mentioned. One reason can be their relatively weak attractiveness in the evacuation, which is proved by the sorted list. The other reason can be the prevalence of the three architectural elements, which will draw the evacuee's attention from any other elements aside in the view. In fact, the three architectural elements: Up Stair, Exit, and Doorway Entrance, form the skeleton of the space design, which offer the three related kinds of local architectural cues in the following research.

3.3 Observation on the Evacuation Behavior

To answer the second question in the end of Chapter 2, a VR-based platform is built to observe the evacuation behavior driven by the three local architectural cues selected from the above questionnaire survey, through which the cognition rules and the related events of these local architectural cues can be deduced.

As it is argued in Chapter 2, there are several aspects influencing the choice of the suitable VR techniques. After trials of the normal computer screen with the horizontal view field around 45 degree, Barco wide stereo screen system with the horizontal view field around 74 degree, and Head CAVE system with the horizontal view field around 170 degree (Sun, de Vries, & Dijkstra, 2007), it is believed that the view field is the most important factor for the VR-based observation platform. Thus, a special CAVE platform (Appendix C) is built to observe the virtual evacuation behavior.

3.3.1 Overview

During September 17th 2007 - Jan 23rd 2008, 429 students (201 males and 228 females with the average age at 20, SD=0.9) from College of Architecture and Urban Planning, Tongji University, Shanghai, China participated in the virtual evacuation observation experiment.

3.3.2 Design of the Observation Experiment

To observe the evacuation behavior systematically, it is assumed that the evacuee's choosing process for the cue with the highest probability on any number of cues in the view can be interpreted as a sorting process through a set of paired comparisons on any two cues in the view. Without a fixed number of cues in the view, the combination of the cues can be infinite, which makes the systematic observation impossible. Thus, six kinds of cue pairs with the selected three local architectural cues are used to deal with the infinite combinations in the view. These cue pairs are: Doorway Entrance and Doorway Entrance (D-D), Doorway Entrance and Exit (D-E), Doorway Entrance and Up Stair (D-S), Exit and Exit (E-E), Exit and Up Stair (E-S), Up Stair and Up Stair (S-S).

As a result, to observe the virtual evacuation behavior is to observe how evacuee makes choices in any of these six cue pairs and how the evacuee responds to the chosen cues. For such an observation, the starting points of the virtual evacuation and the stimulation in the experiment are designed purposefully.

1) Distribution of the Starting Points

Fourteen starting points are set to include all the six kinds of cue pairs in the view. Although the largest public underground space in Shanghai (Appendix D) is used as the virtual site for the CAVE platform, the proper starting points have to be found. From these points the visitors will probably start evacuation, such as seats, shops, or parking places. Furthermore, the cue pairs in the view from the starting points should cover all the six kinds of cue pairs. Finally, the fourteen starting points covering all the cue pair types are found (Table 3.3-1).

Table 3.3-1 Distribution of the starting points

| Starting Point | D-D | E-E | S-S | D-E | D-S | E-S |
|----------------|-----|-----|-----|-----|-----|-----|
| I | √ | | | | | |
| II | √ | √ | | √ | | |
| III | √ | | | | √ | |
| IV | √ | | √ | | √ | |
| V | √ | | | | | |
| VI | √ | | | | | |
| VII | √ | | √ | √ | | √ |
| VIII | | | | √ | | |
| IX | √ | | | | √ | |
| X | | √ | | | | |
| XI | √ | √ | | √ | √ | √ |
| XII | | √ | | √ | | |
| XIII | | √ | | √ | √ | √ |
| XIV | | | | | | √ |

2) Interactive Interface

A programmable virtual reality engine (Vega v3.7) supports the interactive interface of the experiment, which can offer visual and audio stimulation according to the participant's operation and record their traces automatically. Several aspects are designed carefully to stimulate the participant's evacuation behavior and avoid other interferences.

The visual virtual scenario (Fig.3.3-1) is designed according to the visual cues mentioned in the end of Chapter 2. The scene is rendered according to the perspective principles to provide the visual cue of Overlay and Linear Perspective. The participant can move in the virtual environment dynamically to have the visual cue of Movement Parallax and Motion Perspective. The participant's eye height is fixed at 1.75 meter above the floor by the Height Adjustor to support the visual cue of Height in Visual Field. The participant can always see the square pavement on the floor to have the visual cue of Size. The participant can find Doorway Entrance by the different Shade of the wall. All these visual cues can improve the participant's spatial perception.

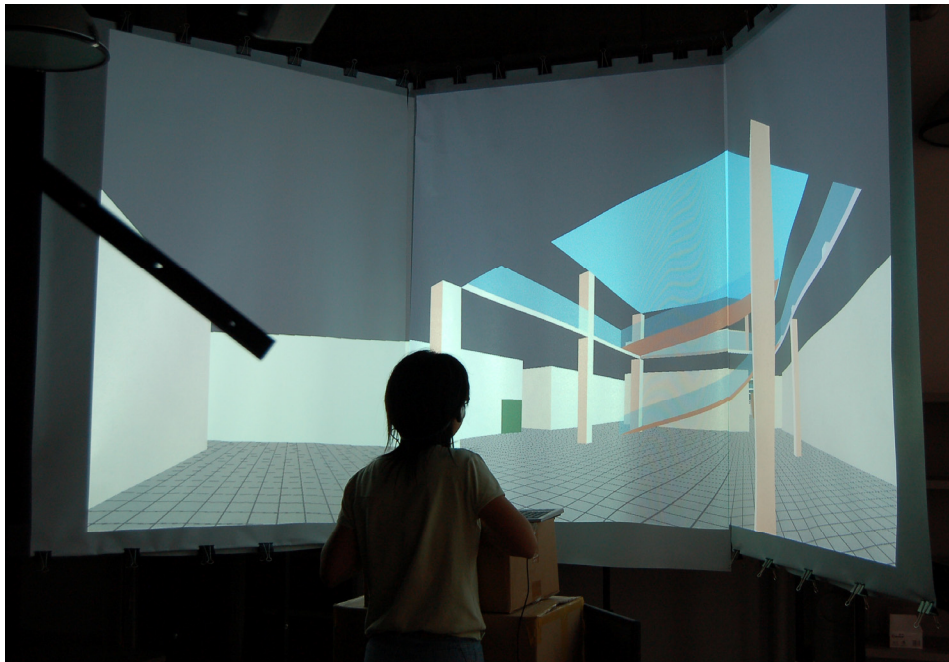


Figure 3.3-1 Virtual scene in the observation experiment

Besides these visual cues, the virtual scene is presented in a very abstract way, which only offers the three-dimensional geometric features of the three local architectural cues. Exit is a symbolic rectangular in green, Up Stair is a symbolic ramp in brown, and Doorway Entrance can be distinguished according to the perspective relationship and the different shade of the wall surfaces. There is no non-geometric difference between any two cues in the same type. All the other cues, such as signs, moving people, growing smoke, are avoided in the scene.

To impose the psychological pressure to the participants, a noisy sound mixed by the alarm, the running steps, and the heart beating can always be heard through the ear phone during the whole virtual evacuation to make them strained. Meanwhile, the participants are told to evacuate as quickly as possible. Their performance will be recorded by the computer. A high score can lead to some prize.

To avoid the operational preferences of the mouse or the arrow keys controlled by one hand, the participants are asked to use the both hands, the left one on key Z to turn left and the right one on key M to turn right. The key Space Bar in the middle is used to run forward.

3.3.3 Procedure

With a limited number of participants, the observation is implemented in two sections to increase the number of valid traces. The definition what is the safety as the termination of an evacuation task makes the number of the traces in an ideal observation equal to the number of the participants. Every participant should be told to evacuate only once from one of the fourteen starting points to the safety according to his own definition. He may prefer an Exit than an Up Stair to the ground floor, or the opposite. No matter which one he prefers more like the safety, the experiment staff will stop the observation, when he arrives at it. At this moment, the termination itself reinforces his preference, which will influence the participant's choice on the cue pair of Exit and Up Stair in the next time. Thus, this participant can only be used once in the ideal observation. However, the fourteen starting points are divided into two groups according to whether the participant has the

opportunity to see and to make choice on the cue pair of Exit and Up Stair. In one group of the starting points with the possibility to involve the choice on the cue pair of Exit and Up Stair, the participants are expected to evacuate from only one of the starting points in the group. In the other group of the starting points without the possibility to involve the choice on such a cue pair, the participants are expected to evacuate from all the starting points in the group. In the latter group, the participant's preference between Exit and Up Stair will not influence his choices on the other kinds of cue pairs. Thus, he can produce the evacuation trace for every starting point in this group, which increases the valid traces in the observation experiment. In the following, the process of the two experiment sections is described corresponding to the two groups of the starting points.

In both sections, after the experiment staff adjusts the participant's eyes to the ideal observation position, the participant is asked to practice the navigation in the CAVE system first in a special training virtual environment, which is a separate part of the virtual site. During the practice, the symbolic Exit as a green rectangular and Up Stair as a brown ramp are learned. After ready for the virtual evacuation, he is asked to listen to a recorded direction, in which he is asked to imagine himself staying in the underground space on the west of Huangpu River in the city. The fire alarm urges all the persons to evacuate as soon as possible. Most persons have evacuated successfully. It seems he is the only person in this space.

In the first section, 118 participants evacuate from ten of the fourteen starting points (I, II, III, IV, V, VI, VIII, IX, X, XII) one by one (Table 3.3-1). On these starting points the participant will not see the cue pair of Exit and Up Stair. The definition of the safety is told to the participants explicitly that the evacuation task will terminate when he arrives at an Exit or an Up Stair to the ground floor.

After this section, out of my expectation, it is found that more than half the participants from the starting points III (68.6%) and IX (95.7%) make choice on the cue pair of Exit and Up Stair at some points on the traces. And the participants far less than half from the starting points V (18.6%) and VI (5.1%) have to make choice on such a cue pair at some points on the traces. Thus, the decision is made that the ideal observation for the starting points III and IX will be done again in the second observation section.

In the second section, 311 participants evacuate from six starting points (III, VII, IX, XI, XIII, and XIV). Every participant just implements one evacuation task from one of these points. It is the participant himself who decides what the safety is more like between Exit and Up Stair. When he arrives at an Exit or an Up Stair to the ground floor, the experiment staff will terminate the task.

After this section, 1,123 traces (118 traces for each the starting point I, II, IV, V, VI, VIII, X, and XII, 52 traces for each the starting point III, VII, IX, XI, and XIII, and 51 traces for the starting point XIV) are collected.

3.3.4 Analysis

After the observation experiment, all the traces are imported to the plans of the site (Fig.3.3-2 ~ Fig.3.3-4). These traces are compiled into fourteen diagrams (Fig.3.3-5 ~ Fig.3.3-18) for the further analysis. In every diagram there is a pink circle with black radius, which indicates the position and orientation of the starting point where the participants set out. The traces in the same direction are combined into a blue line with a special width, which indicates the amount of participants on the trace. There are also a fraction and a percentage in red to annotate the exact number of the participants for each branch.

Architectural Cue Model in Evacuation Simulation for Underground Space Design

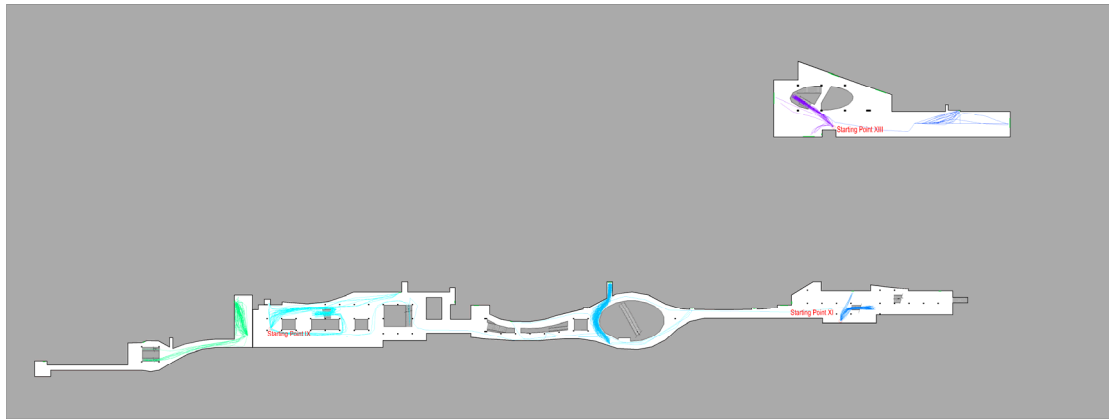


Figure 3.3-2 B1 Plan with traces

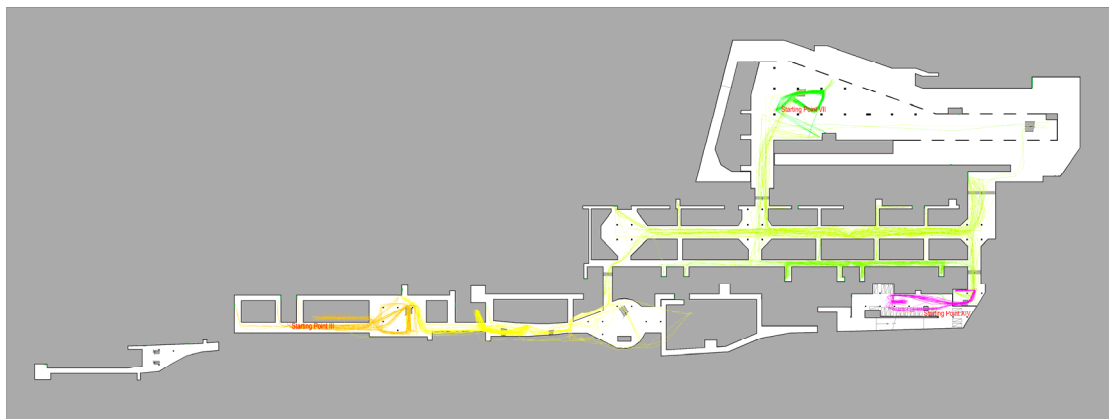


Figure 3.3-3 B2 Plan with traces

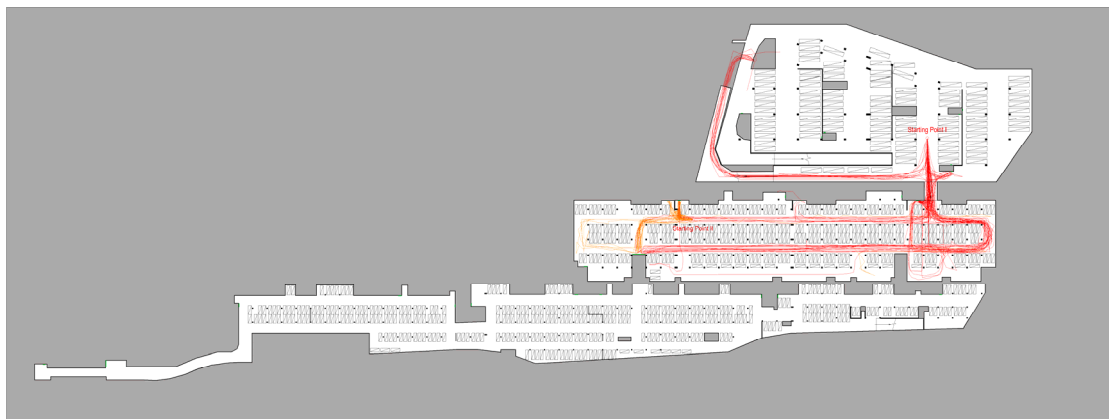


Figure 3.3-4 B3 Plan with traces

To distinguish the different percentages of the participants' propensities in choosing the routes, the following rules are used to depict the percentages in the following analysis.

1. If all the percentages of the routes are less than 50% in one diagram, the participants' propensities for this starting point are regarded "dispersive".

2. If the percentage of one route is less than 50% but more than the average percentage or more than 33.3%, the participants' propensity on this route is regarded "considerable".

3. If the percentage of one route is more than 50%, the participants' propensity on this route is regarded "dominative".

1) Starting Point I

The participants' propensities are dispersive, in which there are two considerable propensities to choose Exit C and Exit D (Fig.3.3-5). The percentages of the five terminations on B3 level are: 13.6% (Stair), 18.7% (Exit A), 3.4% (Exit B), 44.1% (Exit C), and 20.3% (Exit D). No participant turns back to B3 level, after they go upstairs through Stair A.

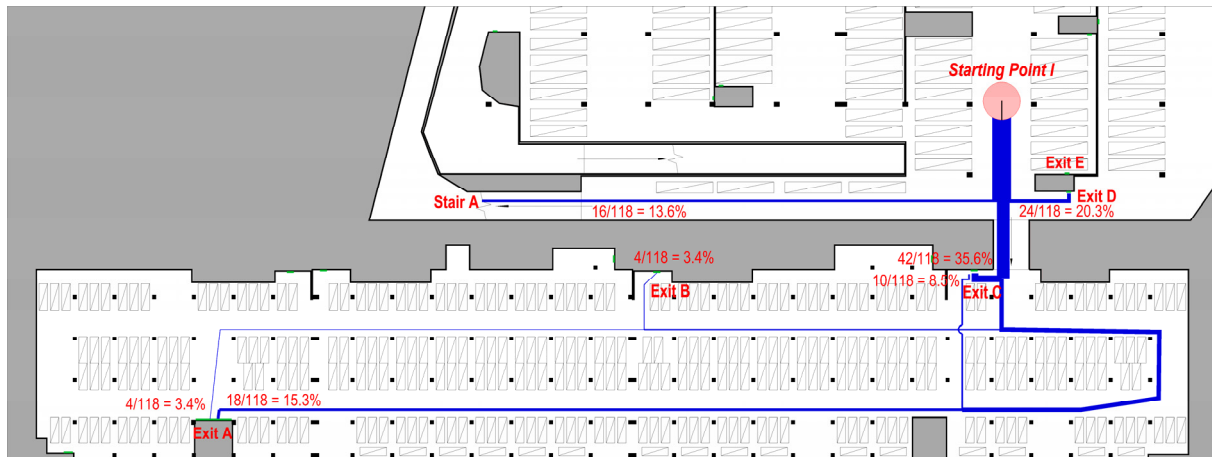


Figure 3.3-5 Traces from Starting Point I

No one chooses the global nearest Exit E hidden behind the coaches for its invisibility in the view field. Moreover, at the first crossover, 33.9% (40/118) participants turn their heads and discover the Stair and Exit D. While the other 66.1% (78/118) participants go forward and neglect the two terminations, from which it is concluded that the limitation of the hemispherical human view field influences the visual access to the cues along the evacuation path.

2) Starting Point II

The participants' choices are summarized in Table 3.3-2. There is a dominative propensity to choose Exit C (Fig.3.3-6). The percentages of the three terminations on this parking level are: 25.4% (Exit A), 9.3% (Exit B), and 65.2% (Exit C). The choice between the two close terminations Exit B and C is confusing. After the interviews with the 11 participants choosing Exit B, it is clear that they neglect the Exit C outside their vision focus and discover Exit B by chance when turning the head. Thus, it is plausible to combine the choices of Exit B and Exit C. Then the propensity to choose Exit C is very dominative with a percentage of 74.5%. Obviously, the closer and narrower Exit C is much more attractive than the farther and wider Exit A. And Exit is preferred than any Doorway.

Table 3.3-2 Choice(s) in Starting Point II

| Starting Point | D-D | | E-E | | S-S | | D-E | | | | D-S | | | | E-S | | | |
|----------------|-----|---|-----|---|-----|---|-----|---|---|---|-----|---|---|---|-----|---|---|---|
| | F | C | F | C | F | C | D | | E | | D | | S | | E | | S | |
| | | | | | | | F | C | F | C | F | C | F | C | F | C | F | C |
| II | | | | √ | | | | | √ | √ | | | | | | | | |

Notes: D: Doorway; E: Exit; S: Up Stair; F: The cue is farther and chosen; C: The cue is closer and chosen.

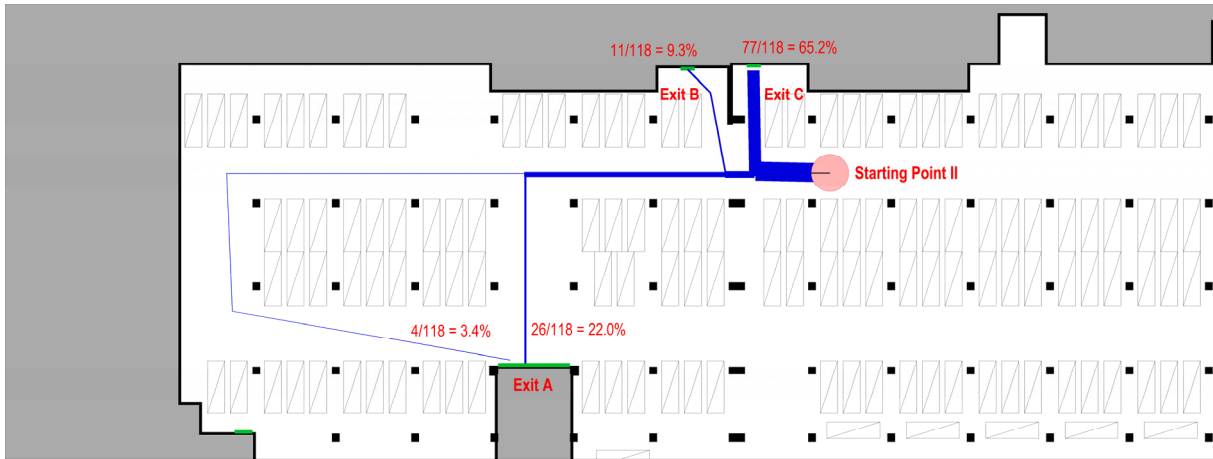


Figure 3.3-6 Traces from Starting Point II

Exit A and C are visible at the starting point. The participants discover them and run round the cars to reach them, from which it is concluded that the participants’ visual perception works at the eye height above the floor and a route plan system working at the height on the floor separately. Any obstacles below the eye height will influence the route plan but not the visual perception just as the cars. Any obstacles higher than the eye height will influence both the visual perception and the route plan just as the coaches.

3) Starting Point III

The participants’ choices are summarized in Table 3.3-3. There is a dominative propensity to choose Stair A (Fig.3.3-7). The percentages of the five terminations on B2 level are: 65.4% (Stair A), 7.7% (Exit A), 5.8% (Exit B), 3.8% (Exit C), and 17.3% (Exit D). No participant turns back to B2 level, after they go upstairs through Stair A.

Table 3.3-3 Choice(s) in Starting Point III

| Starting Point | D-D | | E-E | | S-S | | D-E | | | | D-S | | | | E-S | | | | | | | | | | |
|----------------|-----|---|-----|---|-----|---|-----|---|---|---|-----|---|---|---|-----|---|---|---|---|---|---|---|---|---|---|
| | F | C | F | C | F | C | D | | E | | D | | S | | E | | S | | | | | | | | |
| | | | | | | | F | C | F | C | F | C | F | C | F | C | F | C | | | | | | | |
| | | | | | | | | | | | | | | | | | | | F | C | F | C | F | C | F |
| III | √ | | | | | | | | √ | √ | | | √ | √ | | | | √ | | | | | | | |

Notes: **D**: Doorway; **E**: Exit; **S**: Up Stair; **F**: The cue is farther and chosen; **C**: The cue is closer and chosen.

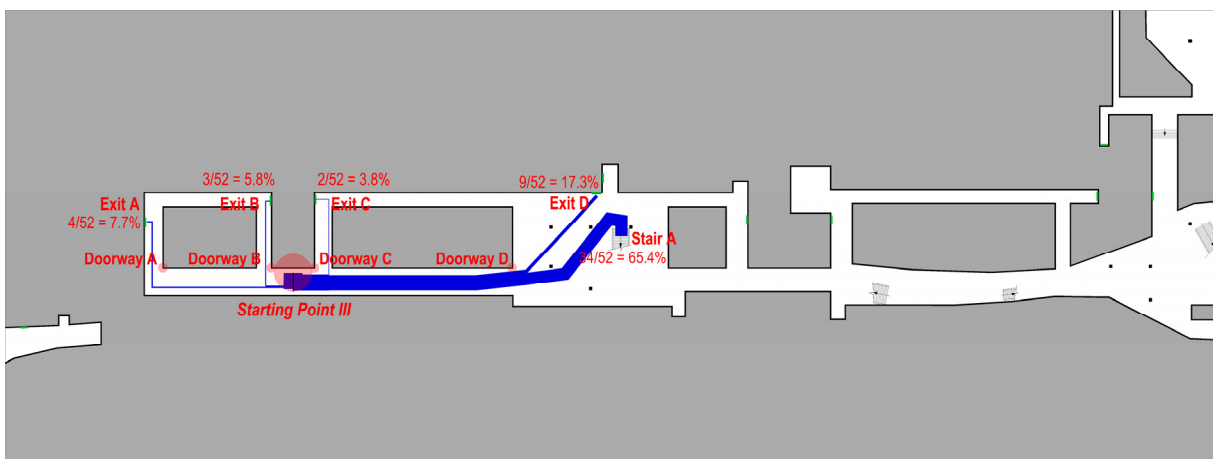


Figure 3.3-7 Traces from Starting Point III

At the starting point, 86.5% (45/52) participants turn to the left toward Stair A, Doorway C, and D rather than turning right to Doorway A and B. The participants are in the middle of Doorway B and C. So the attractiveness of the both doorways is similar. Thus, it is concluded that the attractiveness of either the farther but wider Doorway D or the further Stair A is much stronger than the attractiveness of Doorway A.

Along the evacuation path to Doorway D only 4.4% (2/45) participants choose Exit C, which is one of the nearest exit and on the opposite of the forward direction. Thus, it is concluded the limitation of the hemispherical human view field influences the visual access to the cue along the evacuation path and makes the evacuees miss the global shortest route.

Coming out from Doorway D, 79.1% (34/43) participants choose the closer Stair A rather than farther Exit D. And there is no participant to choose any further Doorway. Meanwhile, during the participants approach Exit A, Exit B, Exit C and Exit D, any Doorway is ignored.

4) Starting Point IV

The participants' choices are summarized in Table 3.3-4. There is a dominative propensity to choose Stair A (Fig.3.3-8). The percentages of the four terminations on B2 level are: 4.2% (Exit A), 80.5% (Stair A), 11.9% (Stair B), and 3.4% (Stair C). No participant turns back to B2 level, after they go upstairs through Stair A or Stair B.

Table 3.3-4 Choice(s) in Starting Point IV

| Starting Point | D-D | | E-E | | S-S | | D-E | | | | D-S | | | | E-S | | | |
|----------------|-----|---|-----|---|-----|---|-----|---|---|---|-----|---|---|---|-----|---|---|---|
| | F | C | F | C | F | C | D | | E | | D | | S | | E | | S | |
| | | | | | | | F | C | F | C | F | C | F | C | F | C | F | C |
| IV | | √ | | | √ | √ | | | √ | √ | | | √ | √ | | | | |

Notes: **D**: Doorway; **E**: Exit; **S**: Up Stair; **F**: The cue is farther and chosen; **C**: The cue is closer and chosen.

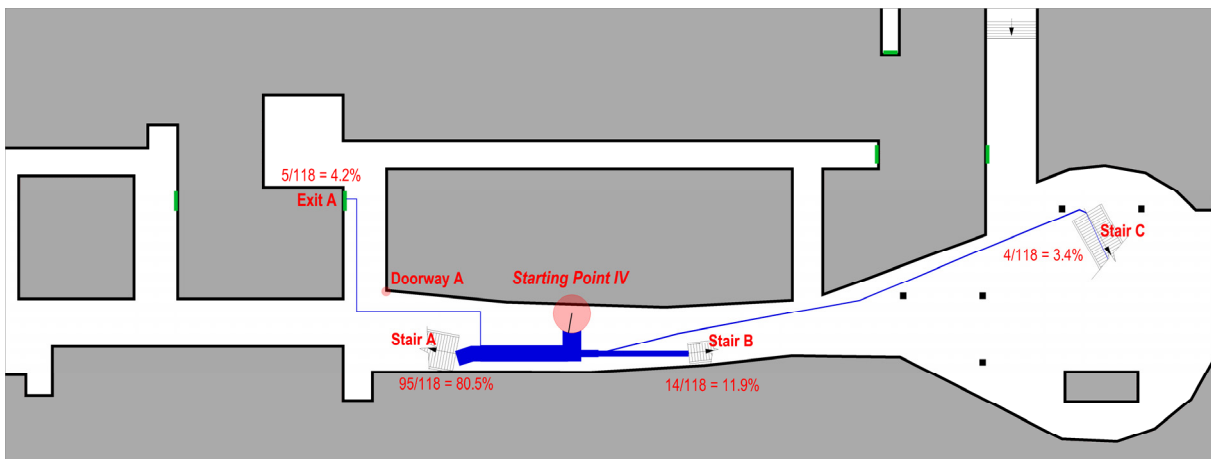


Figure 3.3-8 Traces from Starting Point IV

Although the shortest way to terminate the evacuation is to approach Exit A, only 4.2% participants find this way just because of its invisibility. It is concluded that the visual access from the participant to a cue is the precondition for the cue to be chosen. Meanwhile, these participants are induced by Doorway A first, which is obviously more attractive than the other farther Doorways. When the participants approach Doorway A and notice Exit A, they ignore any other Doorway.

Architectural Cue Model in Evacuation Simulation for Underground Space Design

Facing with the two stairs at the starting point, most participants 89.6% (95/106) chose Stair A rather than Stair B. The only difference between them is the width dimension, from which it is concluded the geometric features of the stair, such as its width, influence the evacuees' route choices. Meanwhile, most participants chose the closer Stair A 95% (95/100) rather than the further Doorway A (5/100). And a few participants choose a far Stair C rather than any closer Doorway.

5) Starting Point V

The participants' choices are summarized in Table 3.3-5. The participants' propensities are dispersive (Fig.3.3-9), in which there are six considerable propensities to choose Stair A, Exit A, Exit B, Exit G, Exit H and Exit K. The percentages of the thirteen terminations on B2 level are: 10.2% (Stair A), 1.7% (Stair B), 8.5% (Exit A), 11.0% (Exit B), 5.1% (Exit C), 4.2% (Exit D), 3.4% (Exit E), 4.2% (Exit F), 25.4% (Exit G), 11.9% (Exit H), 3.4% (Exit I), 2.5% (Exit J), and 8.5% (Exit K). No participant turns back to B2 level, after they go upstairs through Stair A or Stair B.

Table 3.3-5 Choice(s) in Starting Point V

| Starting Point | D-D | | E-E | | S-S | | D-E | | | | D-S | | | | E-S | | | |
|----------------|-----|---|-----|---|-----|---|-----|---|---|---|-----|---|---|---|-----|---|---|---|
| | F | C | F | C | F | C | D | | E | | D | | S | | E | | S | |
| | | | | | | | F | C | F | C | F | C | F | C | F | C | F | C |
| V | √ | | | | | | | | | | | | | | √ | | | |

Notes: D: Doorway; E: Exit; S: Up Stair; F: The cue is farther and chosen; C: The cue is closer and chosen.

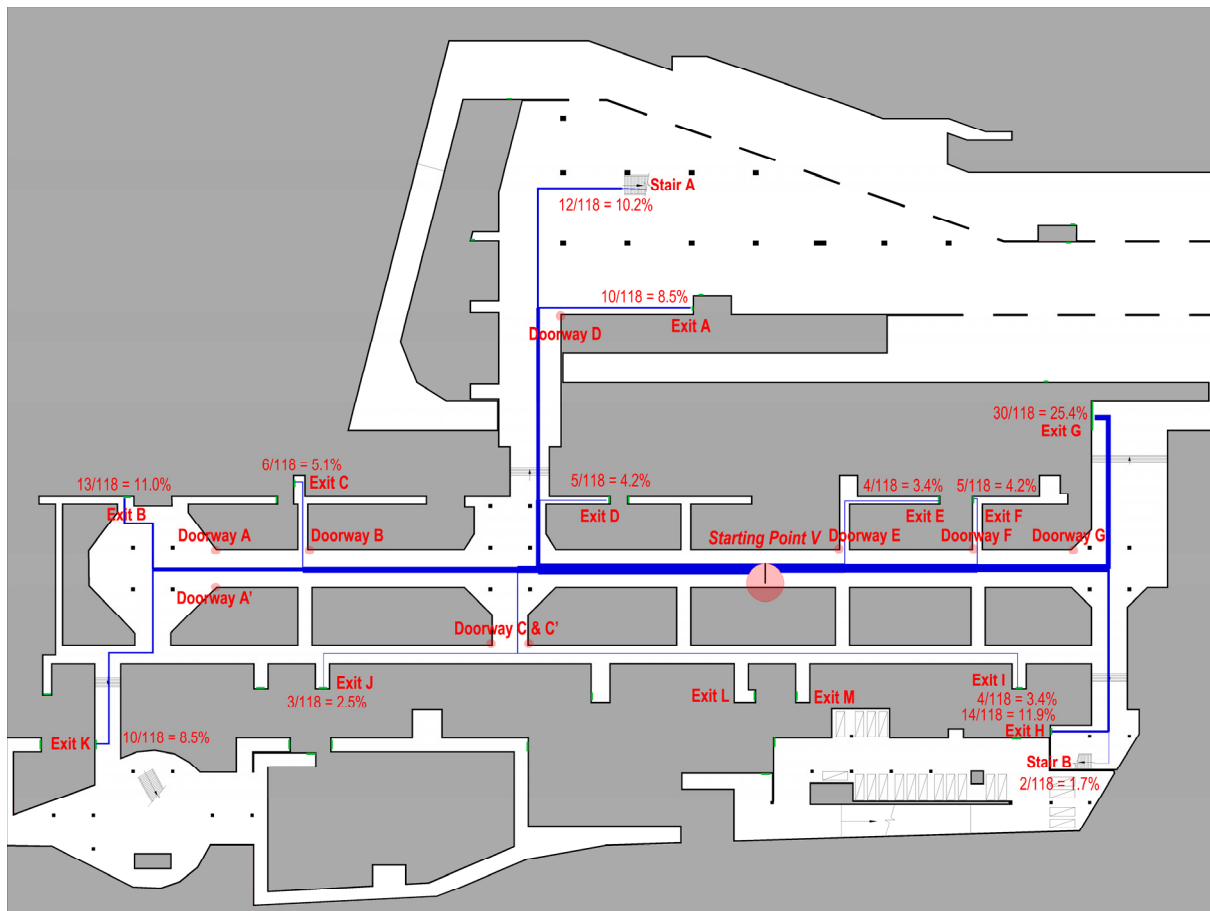


Figure 3.3-9 Traces from Starting Point V

Although the global nearest way to terminate the evacuation is to approach Exit L or M, no participant found this way just because of their invisibility along the evacuation path.

Turning right from the starting point, most participants (30/39) choose the farther but wider Doorway G rather than Doorway E (4/39) or F (5/39). Running to the second crossover on the left of the starting point obviously more participants prefer farther but wider Doorway A&A' (23/58) and D (22/58) rather than the closer but narrower Doorway B (6/58) and C&C' (7/58). It is concluded that the geometric features of the doorway such as its width influence the evacuees' route choices.

More participants choose the farther Exit H (14/16) rather than the closer Stair B (2/16).

6) Starting Point VI

The participants' propensities are dispersive (Fig.3.3-10), in which there are three considerable propensities to choose Exit B, Exit D and Exit E. The percentages of the nine terminations on B2 level are: 5.1% (Stair A), 3.4% (Stair B), 2.5% (Exit A), 27.1% (Exit B), 6.8% (Exit C), 23.7% (Exit D), 19.4% (Exit E), and 3.4% (Exit F). No participant turns back to B2 level, after they go upstairs through Stair A or Stair B.

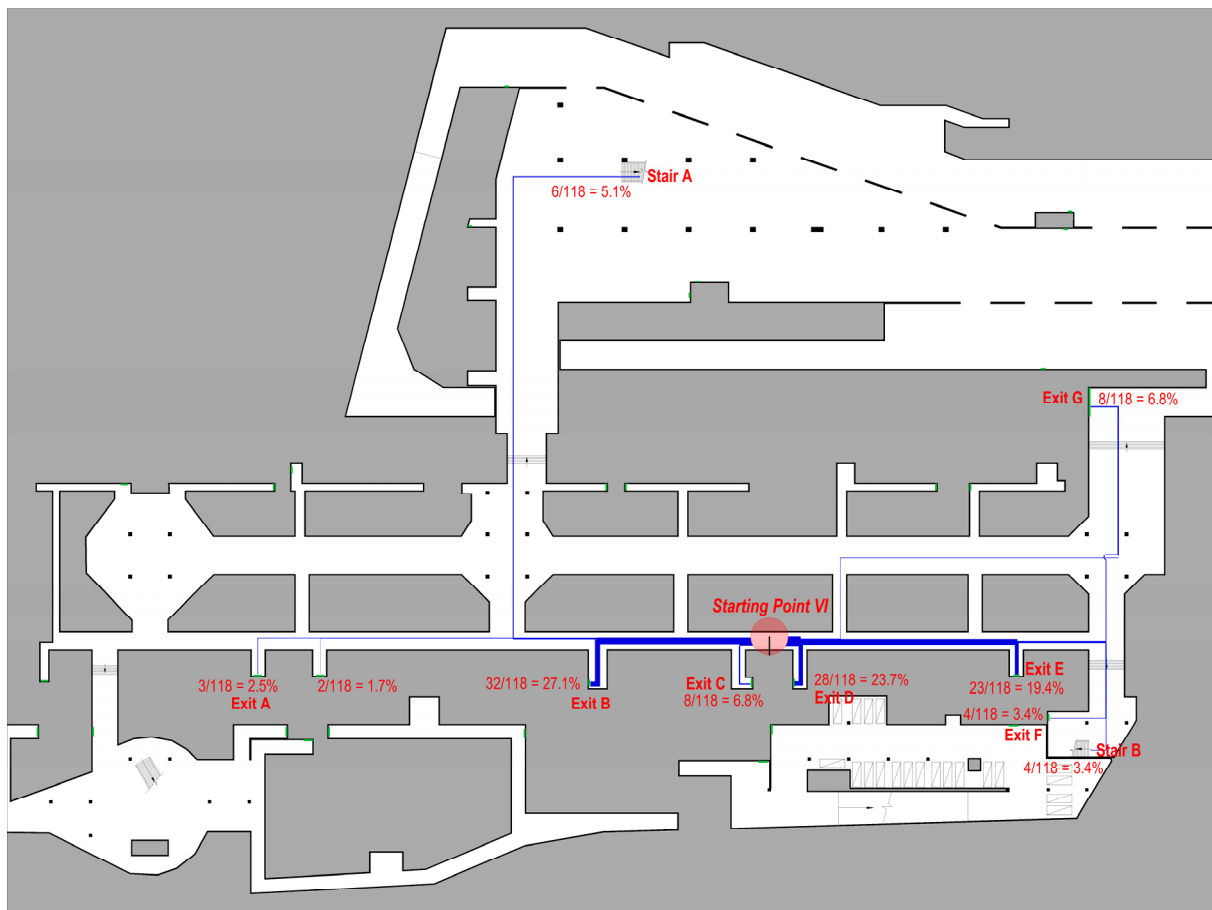


Figure 3.3-10 Traces from Starting Point VI

7) Starting Point VII

The participants' choices are summarized in Table 3.3-6. There is a dominative propensity to choose Stair A (Fig.3.3-11). The percentages of the three terminations on B2 level are: 80.8% (Stair A), 13.4% (Exit A), and 5.8% (Exit B). No participant turns back to B2 level, after they go upstairs through Stair A.

Table 3.3-6 Choice(s) in Starting Point VII

| Starting Point | D-D | | E-E | | S-S | | D-E | | | | D-S | | | | E-S | | | |
|----------------|-----|---|-----|---|-----|---|-----|---|---|---|-----|---|---|---|-----|---|---|---|
| | F | C | F | C | F | C | D | | E | | D | | S | | E | | S | |
| | | | | | | | F | C | F | C | F | C | F | C | F | C | F | C |
| VII | | | | | | √ | | | √ | √ | | | √ | √ | | | | √ |

Notes: D: Doorway; E: Exit; S: Up Stair; F: The cue is farther and chosen; C: The cue is closer and chosen.

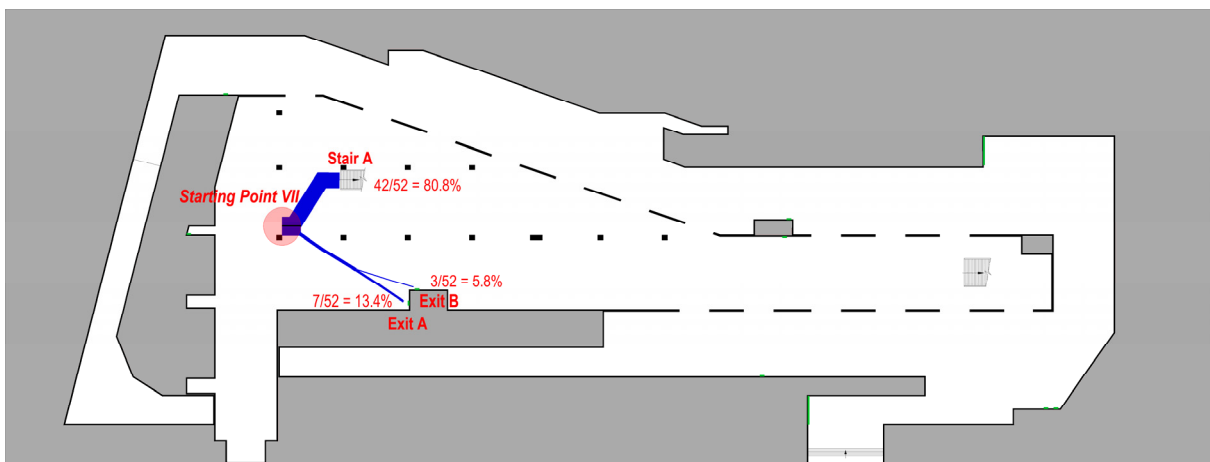


Figure 3.3-11 Traces from Starting Point VII

More participants choose Stair A (42/52) rather than Exit A&B (10/52). The exit is much farther than the stair. Meanwhile, the participants prefer Exit or Up Stair rather than any Doorway.

Although the shortest way to terminate the evacuation is to turn back to approach Exit C, no participant uses this way just because of its invisibility along the evacuation path. The invisibility is caused by the limitation of the hemispherical human view field.

All the participants chose Stair A rather than Stair B. The differences between them are the width, the distance and the orientation in the participants' view, from which it is concluded that a narrower but much closer side stair is more attractive to the evacuees than a wider but much farther one just facing the evacuees.

8) Starting Point VIII

The participants' choices are summarized in Table 3.3-7. There is a dominative propensity to choose Exit A (Fig.3.3-12). The percentages of the two terminations on B1 level are: 92.4% (Exit A) and 7.6% (Stair A).

Without the visual access to Stair A at the starting point, the participants indeed choose Doorway A rather than Stair A at the starting point, from which it is concluded the evacuees have an obvious

propensity to choose the exit much farther and narrower rather than the doorway much closer and wider. However, out of my expectation, still a few participants (9/118) choose Doorway A rather than Exit A to try their luck to explore some potential Exit or Up Stair just behind Doorway A, which might be much closer than Exit A in the view. Meanwhile, when the participants get through Doorway A, all of them choose Stair A rather than any Doorway.

Table 3.3-7 Choice(s) in Starting Point VIII

| Starting Point | D-D | | E-E | | S-S | | D-E | | | | D-S | | | | E-S | | | |
|----------------|-----|---|-----|---|-----|---|-----|---|---|---|-----|---|---|---|-----|---|---|---|
| | F | C | F | C | F | C | D | | E | | D | | S | | E | | S | |
| | | | | | | | F | C | F | C | F | C | F | C | F | C | F | C |
| VIII | | | | | | | | | √ | | | √ | √ | | | | | |

Notes: D: Doorway; E: Exit; S: Up Stair; F: The cue is farther and chosen; C: The cue is closer and chosen.

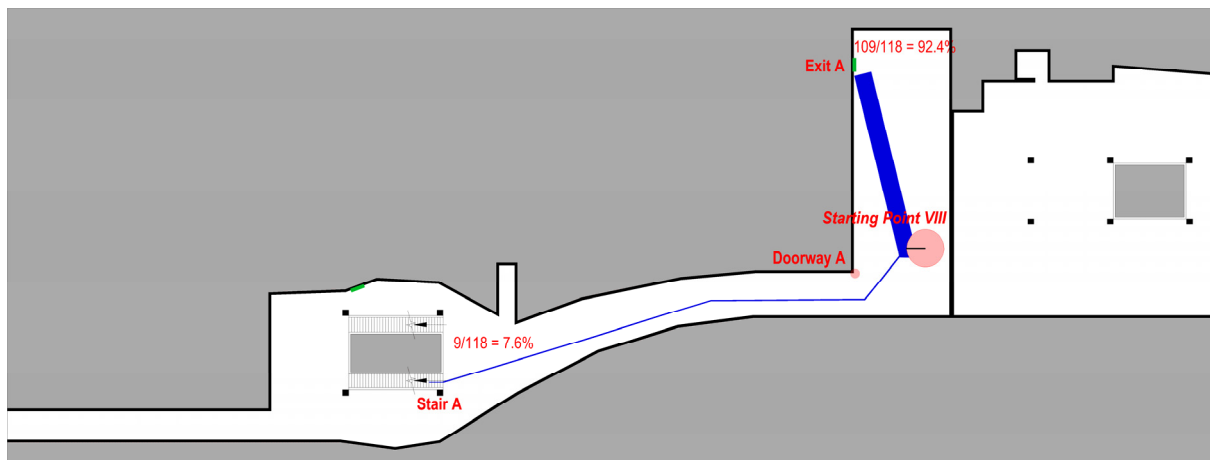


Figure 3.3-12 Traces from Starting Point VIII

9) Starting Point IX

The participants' choices are summarized in Table 3.3-8. There is a dominative propensity to choose Stair A (Fig.3.3-13). The percentages of the three terminations on B1 level are: 82.7% (Stair A), 3.8% (Stair B), and 13.5% (Exit A).

Most participants choose the closer Stair A (43/52) rather than the farther Exit A (7/52) or the farther Stair B (2/52). Meanwhile, when the participants approach Exit A and Stair B, more of them choose the closer Exit A (7/52) rather than the farther Stair B (2/52). Out of my expectation, a few evacuees (3/52) strayed from the route toward Stair A to Doorway A to try their luck to explore a potential Exit or Up Stair just behind Doorway A, which might be much closer than Stair A in the view. Meanwhile, when everything behind Doorway A is clear to the participants at the entrance of it, the participants lose their interest on the Doorway Entrance and turn back to Stair A. It suggests that a Doorway Entrance is only valid or attractive to evacuees when the space behind it is vague. It also suggests that the participants have some memory mechanism storing the information of Stair A although it is outside their vision when they explore Doorway A.

Table 3.3-8 Choice(s) in Starting Point IX

| Starting Point | D-D | | E-E | | S-S | | D-E | | | | D-S | | | | E-S | | | |
|----------------|-----|---|-----|---|-----|---|-----|---|---|---|-----|---|---|---|-----|---|---|---|
| | F | C | F | C | F | C | D | | E | | D | | S | | E | | S | |
| | | | | | | | F | C | F | C | F | C | F | C | F | C | F | C |
| IX | | | | | | √ | | | | | | | | | | √ | | √ |

Notes: D: Doorway; E: Exit; S: Up Stair; F: The cue is farther and chosen; C: The cue is closer and chosen.

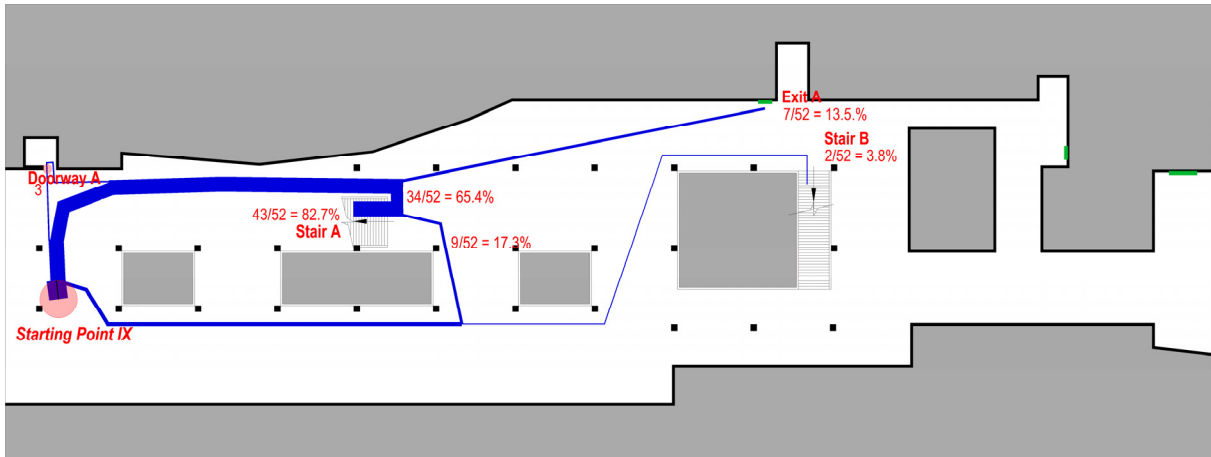


Figure 3.3-13 Traces from Starting Point IX

10) Starting Point X

The participants' choices are summarized in Table 3.3-9. There is a dominative propensity to choose Exit B (Fig.3.3-14). The percentages of the three terminations on B1 level are: 2.5% (Exit A), 94.1% (Exit B), and 3.4% (Exit C). The closer Exit B is chosen rather than any other farther Exit.

Table 3.3-9 Choice(s) in Starting Point X

| Starting Point | D-D | | E-E | | S-S | | D-E | | | | D-S | | | | E-S | | | |
|----------------|-----|---|-----|---|-----|---|-----|---|---|---|-----|---|---|---|-----|---|---|---|
| | F | C | F | C | F | C | D | | E | | D | | S | | E | | S | |
| | | | | | | | F | C | F | C | F | C | F | C | F | C | F | C |
| X | | | | √ | | | | | | | | | | | | | | |

Notes: D: Doorway; E: Exit; S: Up Stair; F: The cue is farther and chosen; C: The cue is closer and chosen.

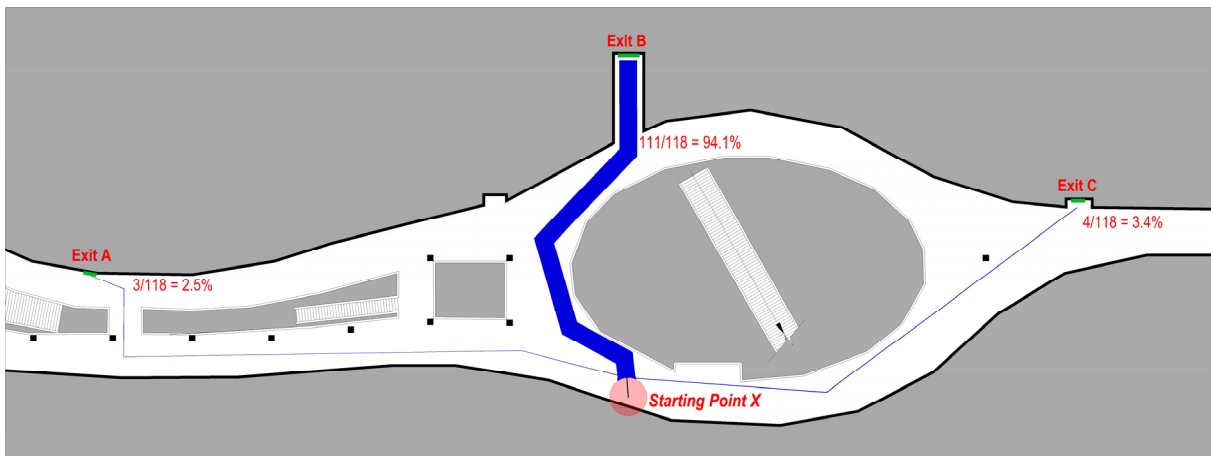


Figure 3.3-14 Traces from Starting Point X

Exit B is visible at the starting point but not reachable directly. The participants discover it and run round the atrium to approach it, from which it is concluded that the participants have a visual perception system working at the eye height above the floor and a route plan system working at the height on the floor separately. It also suggests that the participants have some memory mechanism storing the information of Exit B although it is outside their vision when they walk around the atrium.

11) Starting Point XI

The participants' choices are summarized in Table 3.3-10. There is a dominative propensity to choose Stair A (Fig.3.3-15). The percentages of the two terminations on B1 level are: 9.6% (Exit A) and 90.4% (Stair A). Most participants choose the farther closer Stair A (47/52) rather than the farther Exit A (5/52). Furthermore, the farther Exits and any Doorway are not preferred.

Table 3.3-10 Choice(s) in Starting Point XI

| Starting Point | D-D | | E-E | | S-S | | D-E | | | | D-S | | | | E-S | | | |
|----------------|-----|---|-----|---|-----|---|-----|---|---|---|-----|---|---|---|-----|---|---|---|
| | F | C | F | C | F | C | D | | E | | D | | S | | E | | S | |
| | | | | | | | F | C | F | C | F | C | F | C | F | C | F | C |
| XI | | | | √ | | | | √ | √ | | | √ | √ | | | | | √ |

Notes: D: Doorway; E: Exit; S: Up Stair; F: The cue is farther and chosen; C: The cue is closer and chosen.

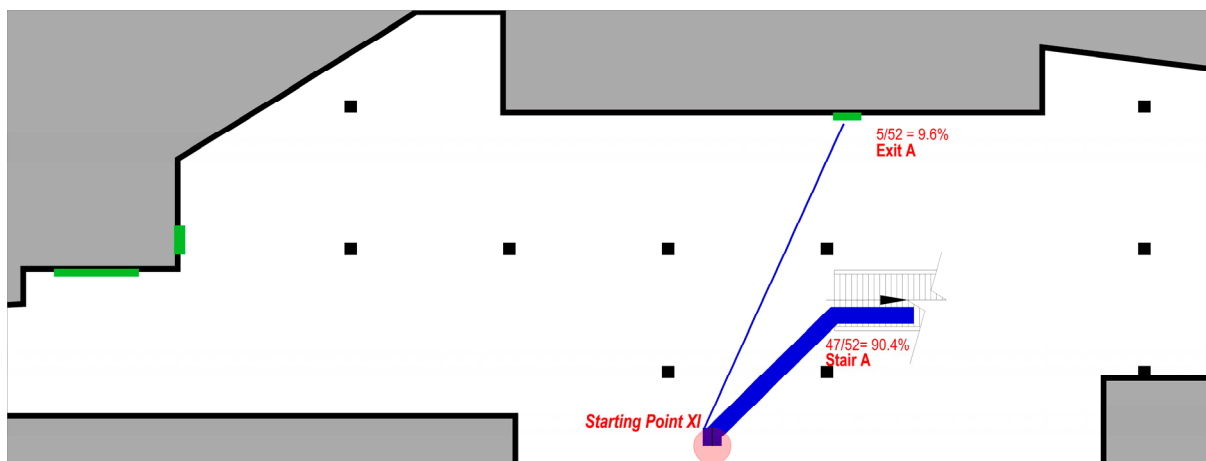


Figure 3.3-15 Traces from Starting Point XI

12) Starting Point XII

The participants' choices are summarized in Table 3.3-11. There is a dominative propensity to choose Exit B (Fig.3.3-16). The percentages of the three terminations on B1 level are: 0.8% (Stair A), 15.3% (Exit A) and 83.9% (Exit B). Much more participants (99/118) choose the farther but wider Exit B rather than the closer but narrower Exit A (18/118), which indicates the evacuees' propensity is influenced not only by the distance attribute but also by the others, such as the width and the angular position in the view. Meanwhile, the closer Doorway behind Exit A is ignored.

Table 3.3-11 Choice(s) in Starting Point XII

| Starting Point | D-D | | E-E | | S-S | | D-E | | | | D-S | | | | E-S | | | |
|----------------|-----|---|-----|---|-----|---|-----|---|---|---|-----|---|---|---|-----|---|---|---|
| | F C | | F C | | F C | | D | | E | | D | | S | | E | | S | |
| | F | C | F | C | F | C | F | C | F | C | F | C | F | C | F | C | F | C |
| XII | | | √ | | | | | | √ | | | | | | | | | |

Notes: D: Doorway; E: Exit; S: Up Stair; F: The cue is farther and chosen; C: The cue is closer and chosen.

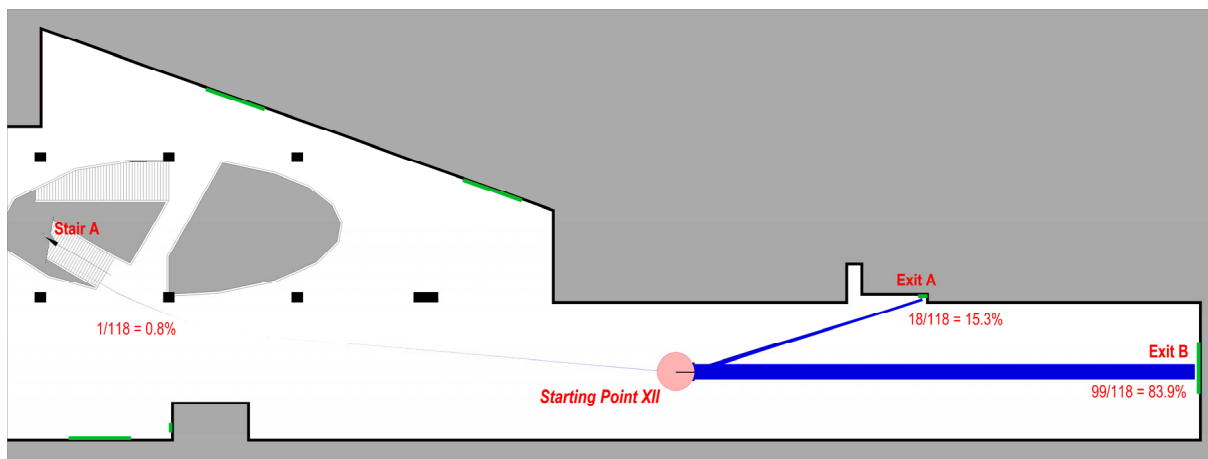


Figure 3.3-16 Traces from Starting Point XII

13) Starting Point XIII

The participants' choices are summarized in Table 3.3-12. There is a dominative propensity to choose Stair A (Fig.3.3-17). The percentages of the three terminations on B1 level are: 3.8% (Exit A), 9.6% (Exit B) and 86.6% (Stair A). Most participants choose Stair A (45/52) rather than the closer Exit B (5/52) and farther Exit A (2/52). Meanwhile, more participants choose the closer Exit B (5/52) than Exit A (2/52). Even the participants to Exit B don't discover another closer Exit with the limitation of the hemispherical human view field.

Table 3.3-12 Choice(s) in Starting Point XIII

| Starting Point | D-D | | E-E | | S-S | | D-E | | | | D-S | | | | E-S | | | |
|----------------|-----|---|-----|---|-----|---|-----|---|---|---|-----|---|---|---|-----|---|---|---|
| | F C | | F C | | F C | | D | | E | | D | | S | | E | | S | |
| | F | C | F | C | F | C | F | C | F | C | F | C | F | C | F | C | F | C |
| XIII | | | | √ | | | | | | | | | | | | | √ | √ |

Notes: D: Doorway; E: Exit; S: Up Stair; F: The cue is farther and chosen; C: The cue is closer and chosen.

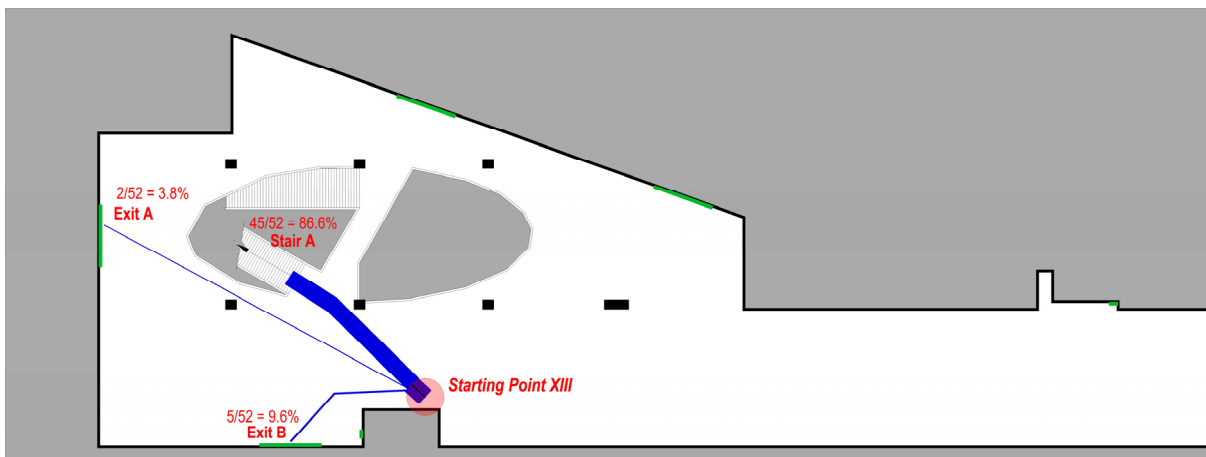


Figure 3.3-17 Traces from Starting Point XIII

14) Starting Point XIV

The participants' choices are summarized in Table 3.3-13. There is a dominative propensity to choose Stair A (Fig.3.3-18). No participant turns back to B2 level, after they go upstairs through Stair A. The percentages of the two terminations on B2 level are: 31.4% (Exit A) and 68.6% (Stair A). With such a choice conflicting with the choice in the analysis of Start Point V, it is believed that the preference between the cue pair of Exit and Up Stair needs further investigation.

Table 3.3-13 Choice(s) in Starting Point XIV

| Starting Point | D-D | | E-E | | S-S | | D-E | | D-S | | E-S | | |
|----------------|-----|---|-----|---|-----|---|-----|---|-----|---|-----|---|---|
| | F | C | F | C | F | C | D | E | D | S | E | S | |
| | | | | | | | F | C | F | C | F | C | F |
| XIV | | | | | | | | | | | | | √ |

Notes: D: Doorway; E: Exit; S: Up Stair; F: The cue is farther and chosen; C: The cue is closer and chosen.

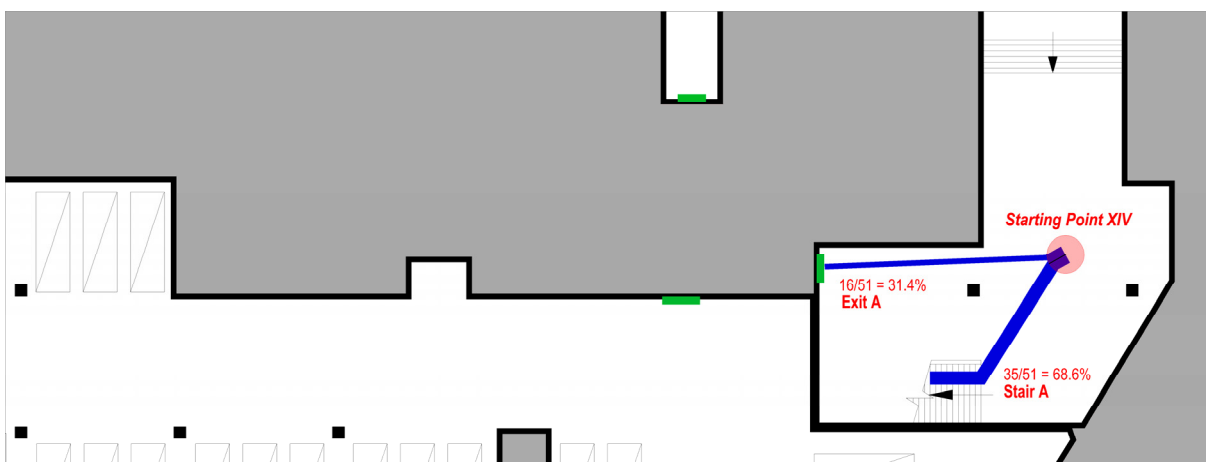


Figure 3.3-18 Traces from Starting Point XIV

3.3.5 Conclusions

Through the observation experiment in the CAVE platform, not only two kinds of knowledge, namely cognition rules and related actions related to the three selected local architectural cues, are deduced just as planned in the very beginning of this experiment, but also several other issues are revealed, which are discussed below.

1) Cognition Rules and Related Events

The evacuees perceive the local architectural cues in abstract forms and approach them.

To deduce the knowledge about the cognition rules of the three local architectural cue types, a set of rules is used to design the symbolic forms in an abstract level to present the three architectural elements. In fact, in the research context, the design rules of the cognizable abstract forms are deduced for the three architectural elements in the CAVE platform, instead of their cognition rules in real world. It must be ensured that any abstract form designed according to these rules can be understood by the participants as a certain architectural element in the CAVE platform. If these rules can work in the current observation experiment, they can also work in the following experiment for the systematic measurement. Obviously, through out the observation, all the participants can cognize the three kinds of architectural elements in their view according to the design rules (Table 3.3-14).

Table 3.3-14 Cognitive rules and related actions of the three local architectural cues

| Local Architectural Cue | Cognition / Design Rule(s) | Related Action(s) |
|--------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------|
| Up Stair | A walkable slope face linking the current floor to a higher floor with the width larger than the human body | Approach the linkage between the slope and the current floor. Climb the slope to reach the higher floor. |
| Exit | Distinguishable Rectangular face on the wall with the dimension larger than the human body. | Approach it. Try to go through with it. (At this moment the task is terminated by the experiment staff.) |
| Doorway Entrance | An opening in the continuous wall surface in the view, which leads to some invisible walkable space behind the vertical edge of the opening. One side of the edge is a closer wall surface. The other side of it is a farther wall surface. | Approach the opening. Explore the space behind the vertical edge for other local architectural cues. |

To deduce the knowledge about the related actions of the three local architectural cue types, it is observed how the evacuees behave after they perceive them. As it is discussed in the evacuation process, “Cue-Choice” model, in Chapter 2, the participants perceive the all the cues, choose one, and take the actions related to the chosen cue. Through out this observation, the first related action to a chosen cue is to approach it. Afterwards, different further actions may be taken according to the specific cue type (Table 3.3-14).

2) Various Preferences in Six Kinds of Cue Pairs

The evacuees’ choices on the six kinds of cue pairs reflect their different preferences on them. These choices on the different cue pairs in every Starting Points (Table 3.3-2 ~ Table 3.3-13) are summed up to create an over view on the evacuees’ choice preference for the different cue pairs (Table 3.3-15).

Table 3.3-15 Choice(s) in the fourteen Starting Points

| Starting Point | D-D | | E-E | | S-S | | D-E | | | | D-S | | | | E-S | | | |
|----------------|-----|---|-----|---|-----|---|-----|---|---|---|-----|---|---|---|-----|---|---|---|
| | F | C | F | C | F | C | D | | E | | D | | S | | E | | S | |
| | | | | | | | F | C | F | C | F | C | F | C | F | C | F | C |
| I | | | | | | | | | | | | | | | | | | |
| II | | | | √ | | | | | √ | √ | | | | | | | | |
| III | √ | | | | | | | | √ | √ | | | √ | √ | | | | √ |
| IV | | √ | | | √ | √ | | | √ | √ | | | √ | √ | | | | |
| V | √ | | | | | | | | | | | | | | √ | | | |
| VI | | | | | | | | | | | | | | | | | | |
| VII | | | | | | √ | | | √ | √ | | | √ | √ | | | | √ |
| VIII | | | | | | | | | | √ | | | √ | √ | | | | |
| IX | | | | | | √ | | | | | | | | | | √ | | √ |
| X | | | | √ | | | | | | | | | | | | | | |
| XI | | | | √ | | | | | √ | √ | | | √ | √ | | | | √ |
| XII | | | √ | | | | | | √ | | | | | | | | | |
| XIII | | | | √ | | | | | | | | | | | | | √ | √ |
| XIV | | | | | | | | | | | | | | | | | | √ |

Notes: **D**: Doorway; **E**: Exit; **S**: Up Stair; **F**: The cue is farther and chosen; **C**: The cue is closer and chosen.

The choice between the cues with the same type depends on not only the distance attribute but also some other attributes. Looking at the table, it is found that no matter the cue in a pair is further or closer than the other cue with the same cue type, such as in the cue pair D-D, E-E, and S-S, it always has the opportunity to be chosen by most of the participants. From the analysis of Starting Point V, it is revealed that besides the distance attribute, the width attribute of Doorway Entrance influences the evacuees’ choices. From the analysis of Starting Point IV, it is revealed that besides the distance attribute, the width attribute of Up Stair influences the evacuees’ choice. From the analysis of Starting Point XII, it is revealed that besides the distance attribute, the width and the angular positions of Exit in the view influence the evacuees’ choice.

Most of the evacuees have the obvious propensity to choose Exit or Up Stair rather than Doorway Entrance, although there are a very few participants try their luck to choose a much closer Doorway Entrance rather than Exit or Up Stair from Starting Points VIII and IX. Looking at the table, it is believed that no matter the Exit or Up Stair is closer or farther than Doorway Entrance, it is always

chosen by the majority.

Looking at this table again, it is found that the propensity of the choices between Exit and Up Stair is not clear, sometimes even conflicting according to the analysis of Starting Points V and XIV. It seems that there must be some other attributes influence the choice beside the cue type and the distance.

Thus, it is concluded that the choice preferences of the four cue pairs (D-D, E-E, S-S, and E-S) should be investigated systematically in the following research. More attributes should be considered besides the distance attribute. Meanwhile, it is assumed for the cue pairs D-E and D-S that the most evacuees will choose Exit or Up Stair rather than any Doorway Entrance.

3) Memory Mechanism

As it is analyzed in Starting Point IX and X, the evacuees have a memory mechanism, which enables them to turn back from a dead end and to take a round route leaving the selected cue out of their vision for a while. Just as the evacuees can remember the cues during the movement, they also seem to be able to forget some outdated cues to speed up the decision making.

From the analysis of Starting Point I, III, IV, V, VI, VII, and XIV, it is found that the evacuees never turn back to the former floor after going upstairs. It means that all the cues in the former floor are never used in the decision making, just like being forgotten, after the evacuees use an Up Stair.

Meanwhile, from the analysis of Starting Point III, IV, V, VI, and VIII, it is found that the evacuees never use the same Doorway Entrance more than once. From these phenomena it is deduced that when the evacuee passes through a Doorway Entrance, it is forgotten. The Doorway Entrance seems attractive to the evacuee only for its possibility to hold any other cue in the space behind it. When the evacuee passes through the Doorway Entrance, the space behind it is completely perceived. Thus, the Doorway Entrance itself loses the attractiveness as a cue. In other words, it is forgotten in the evacuee's following decision process with cues. Moreover, it is deduced that when the evacuee arrives at a selected Doorway Entrance, all the Doorway Entrances remembered before it are forgotten. The fact that the evacuee enters a selected Doorway Entrance means that all the other Doorways perceived before his entering is less attractive than this one. According to the phenomena that no evacuee turns back his way, these less attractive Doorway Entrances are never used. In other words, they are also forgotten in the evacuee's following decision process with cues.

4) A Measurable Component and a Random Component

From all the analyses, it is noticed that the propensities from every starting point indicate a combination of the shared preference and the individual disparity in the evacuation behavior. The shared preference can be systematically measured, and the individual disparity can be treated as a random component.

In a few cases such as from Starting Point I, V, VI, the set of dispersive propensities indicates different preference shared by the different group of people, from which it is deduced that the evacuees making decisions with more Doorway Entrances have some weak preference shared or much randomness.

In most cases such as from Starting Point II, III, IV, VII, VIII, IX, X, XI, XII, XIII, XIV, the dominative propensity indicates one rule shared by more than half the evacuees, from which it is deduced that the evacuees making decisions with more Exit and Up Stair have the strong preference shared and a little randomness.

Together with the dispersive or dominative propensity, there are sometimes a few considerable propensities indicating some preferences not neglectable, such as in the cases of Starting Point I, V, VI, from which it is deduced that the evacuees making decisions with a mixture of Doorway Entrance, Up Stair and Exit have the moderate preference shared and medium randomness.

Thus, it is concluded that no matter what information, clear or vague, is perceived from the local architectural cue, the evacuees' behavior is always driven by a combination of shared preference and the individual randomness. As suggested in the end of Chapter 2, the Conjoint Analysis approach is the suitable method to deal with such a combination of the systematic measurable component and the random component for the following research.

5) Limited View Field

The evacuees' decisions depend on the visual access limited by their view field. With only symbolic architectural elements in an abstract level displayed in the CAVE platform, the participants' evacuation behavior must be driven by the visually perceived local architectural cues from these elements. Thus, their decisions depend on their visual access limited by their view field just as discussed in Chapter 2. From the analysis of Starting Point I, III, IV, V, VII, XIII, it is concluded that evacuee will only use the local architectural cues inside his view field and leave the invisible, sometimes unfortunately the global nearest safety, out of his decision in every step.

6) Visual Access and Route Planning

The visual access and the route planning work on different height. From the analysis of Starting Point II and X, it is concluded that the evacuees' visual perception works on the height of the eyes and is limited by human beings' hemispherical view field. While the tactile perception works on the height of the feet, which avoids bumping on the obstacles in the way.

7) Reliable Behavior in the Observation

The evacuees' traces reflect the reliable behavior in the CAVE platform. With the literature study suggesting that the CAVE system is the most suitable platform to observe the evacuation behavior in the research context, it is necessary to check the reliability of the CAVE platform. It is noticed that the dominative propensities (Starting Point II, III, IV, VII, VIII, IX, X, XI, XII, XIII, and XIV), or considerable propensities (Starting Point I, V, and VI) or even the dispersive set of propensities (Starting Point I, V, and VI) all reflect the participants' shared preferences to some extent. It means that the observed evacuation behavior is repeatable. In fact, these observed traces will be used as the reference to validate the proposed model in the end of this research.

3.4 Framework of the Model

To answer the third question in the end of Chapter 2, a model framework is composed to transform the conclusions derived in Chapter 2 and the above two surveys into a computational model.

3.4.1 Overview

The model framework (Fig. 3.4-1) is supported by the conclusions derived in Chapter 2 and the above two surveys at three levels: the strategy level, the process level, and the cue level.

At the strategy level, the model framework depends on one of the three evacuation strategies (Section 2.2.2) that the evacuee searches the route to the safety without a plan or known destination in the research context of the complex public underground space designs. Thus, in this research the computational model only uses the local architectural cues.

At the process level, the model framework inherits the five phases (Fig.2.1-1) from the evacuation “Cue-Choice” process model (Section 2.2.3). Thus, the computational model in this research also has the five phases: “Start Evacuation”, “Check Arrival Cues”, “See”, “Choose”, and “Move” to implement the strategy in a stepwise sequence.

At the cue level, the model framework mimics the human behaviors on cues in the above five phases, which includes perceiving the cue, remembering or forgetting the cue, making decisions on the cues, and moving to the cue etc. Actually, all these computational components at the cue level are developed for the five phases to start the evacuation, to check arrival cues, to see, to choose, and to move. The details of them are introduced in the following.

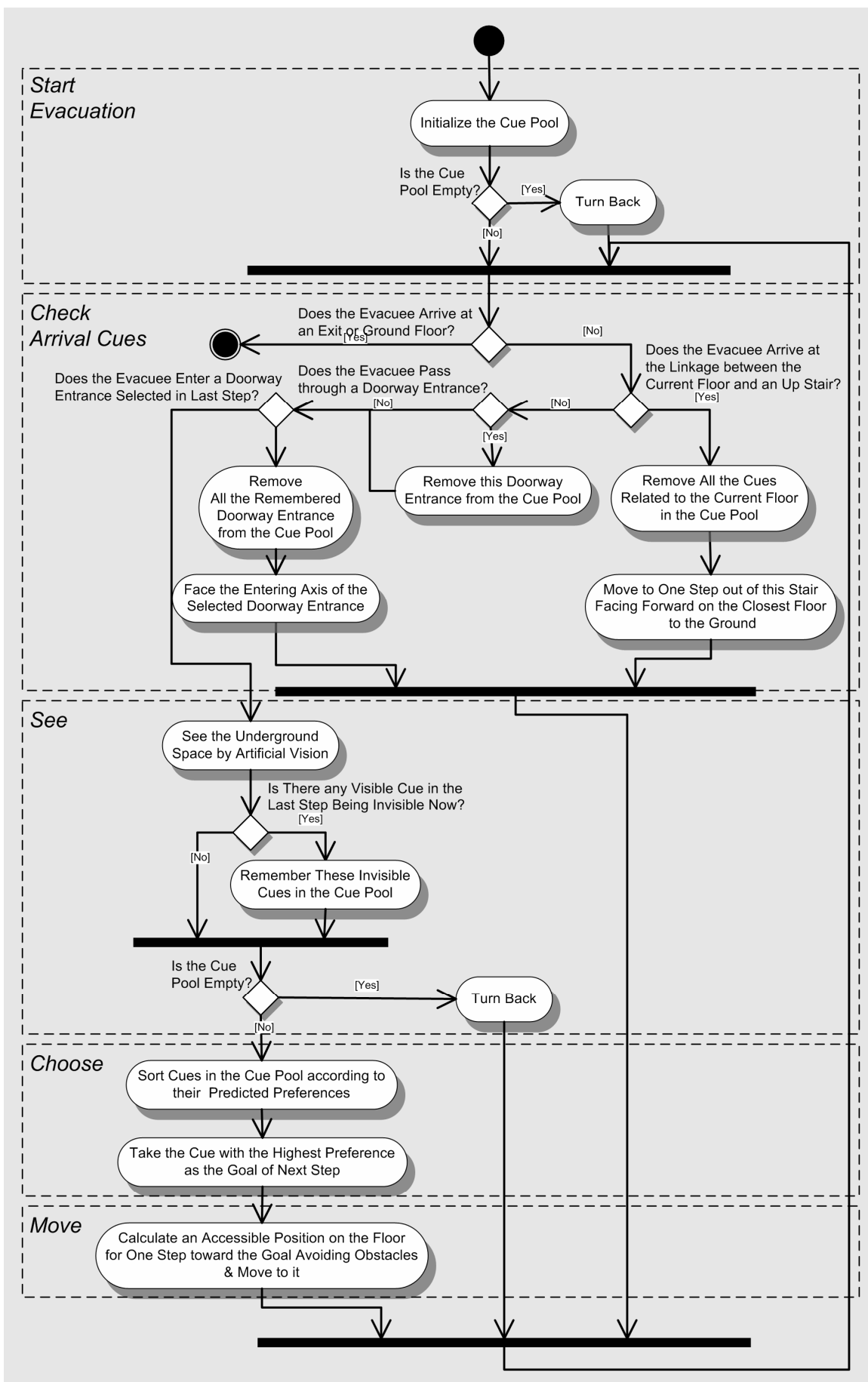


Figure 3.4-1 Model framework

3.4.2 “Start Evacuation”

In this phase the simulated evacuee prepares for the information necessary to start the evacuation, which will only be calculated once. There are two tasks: preparing an empty cue pool as the evacuee’s memory and having a look at the space to perceive the local architectural cues for the first time.

1) Preparing an Empty Cue Pool

According to the conclusion of the previous observation experiment that the evacuees have a memory mechanism, an artificial memory is setup for the perceived and remembered local architectural cues, which is called “Cue Pool”. In fact, according to the only strategy in the strategy level, the simulated evacuee has no experience of the space. Thus, an empty cue pool is prepared for the simulated evacuee.

2) Having the First Look at the Space

According to the conclusions of the previous observation experiment about the limited view field and the height of the visual perception, an artificial vision is defined at a normal height of the human eyes with a limited view field for the simulated evacuee.

Moreover, according to the human visual perception process introduced in Chapter 2, the artificial visual process is built similarly from the light rays to the object notion supported by the cognition rules. The rendering technique of the computer graphics is used to enable the simulated evacuee to perceive the local architectural cues in the space (Fig.3.4-2) as patterns in the pixel array (Fig.3.4-3). The object type information and distance information is attached to the pixel to aid the cognitions of the local architectural cues and their attributes. According to the cognition rules (Table 3.3-14) concluded in the previous observation experiment, the simulated evacuee can use the pixel and the extra information to cognize the three local architectural cues: Up Stair, Exit, and Doorway Entrance and calculate the attributes of them. The detailed cognition algorithms are introduced in Appendix E.

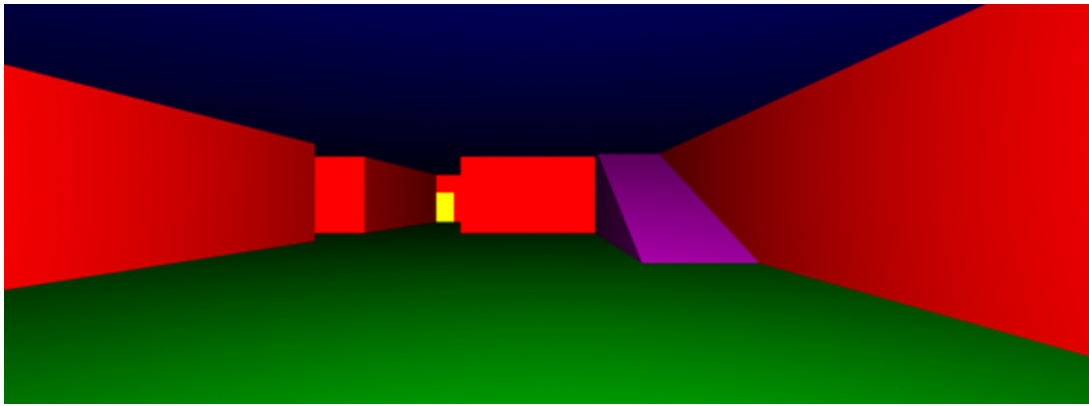


Figure 3.4-2 View in the underground space design

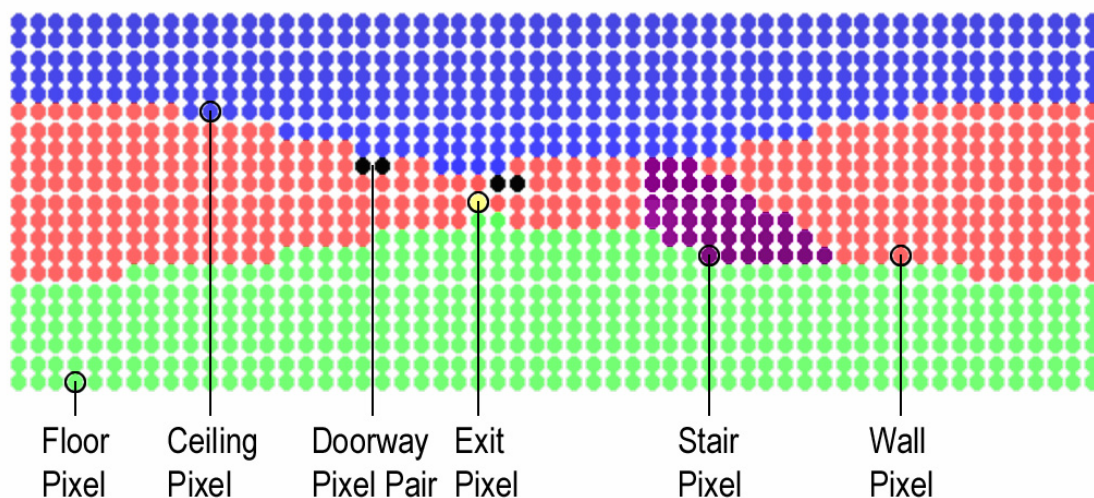


Figure 3.4-3 Pixel array of the artificial vision

After the visual perception process, a post-process is implemented to deal with a bad start in simulation, which means that there is no cue in the limited view field from the starting point. The simulated evacuee checks whether the cue pool is empty. If it is empty, with the almost hemispherical view field introduced in Chapter 2, the best way to search available cues at such a bad starting point is to turn back. Probably the simulated evacuee can find some cues this time to avoid getting stuck at the starting point.

In summary, this phase will be implemented first and for only once in the model. The simulated evacuee will prepare for an empty cue pool and store the perceived local architectural cues in it. An extra check on the cue pool can deal with a bad starting point for the simulated evacuation process. Following this phase, the next four phases form a loop, which is implemented in the simulated evacuee's every moving step.

3.4.3 “Check Arrival Cues”

In this phase the simulated evacuee checks the geometric relationships between him and all the cues in the cue pool, according to which he takes the action correspondingly.

1) Arriving at Safety

The simulated evacuee checks the distance from him to all the Exits and Up Stairs to the ground floor. As defined in the aims of this model, the evacuation behavior of this research is inside the Exit Accesses, which means that when the evacuee arrives at the Exit door or the ground floor through an Up Stair, he is regarded in the safety. Thus, if the distance from the simulated evacuee to any Exit or Up Stair to the ground floor is less than one step, the evacuee is regarded in the safety. When he is in the safety, the whole simulation terminates. If not, the simulated evacuee has to go on checking the other relationships.

2) Arriving at an Up Stair not to the Ground Floor

The simulated evacuee checks the distance from him to all the Up Stairs not to the ground floor. As it is concluded in the previous observation experiment, the evacuee will forget all the cues perceived in the lower floor after he goes upstairs. Thus, if the distance from him to the linkage between the current floor and an Up Stair is less than one step, all the cues perceived on the current floor will be removed from the cue pool, and he will go upstairs through this stair facing forward at the closest floor to the ground floor just as the related actions concluded (Table 3.3-14). Afterwards, the simulated evacuee will skip all the rest process and begin with a new loop for the next step. If there is no such an Up Stair, he will go on checking the other relationships.

3) Passing through a Doorway Entrance

The simulated evacuee checks whether the line segment between his last position and the current position crosses any Doorway Entrance. In other words, he checks whether he passes through a Doorway Entrance. As it is concluded in the observation experiment, the evacuee will forget any passed Doorway Entrance. Thus, if he finds such a Doorway Entrance through this checking process, this cue will be removed from the cue pool. Afterwards, he will go on checking the other relationships, no matter whether such a cue is found or not.

4) Entering a Selected Doorway Entrance

The simulated evacuee checks the distance from him to the selected Doorway Entrance in the last step if there is any. As it is deduced in the observation experiment, the evacuee will forget all the Doorway Entrances remembered before he enters the selected Doorway Entrance. Thus, if he finds the distance is less than one step, all the Doorway Entrances marked “Remembered” in the cue pool will be removed. And the simulated evacuee will turn his head facing the entering axis of the selected Doorway Entrance.

After all these checks, if there is no one met, the simulated evacuee will see the space by his artificial vision in the next phase.

3.4.4 “See”

In this phase the simulated evacuee behaves very similar to the phase of Start Evacuation. He will use the pixel-based artificial vision to perceive the three kinds of local architectural cues and

calculate their attributes. All these information will be stored in the cue pool. The post-process to deal with the bad view containing no cue are the same.

However, there is one difference of the cue pool from the Start Evacuation phase. The cue pool in the phase of See is possible to hold some cues already. Thus, an extra post-process is used here to find the cues that should be kept in the cue pool and marked as “Remembered”. The evacuee will check whether any perceived cue in last step becomes invisible in this step. If there is, such a cue will be still hold in the cue pool with a special mark as being remembered.

3.4.5 “Choose”

In this phase the simulated evacuee pick one cue from the cue pool according to his preference and set it as the goal of next step.

1) Selecting the Cue

According to the decision making model, it is concluded in the research context that the simulated evacuee will estimate the probability leading to the safety of the cues in the cue pool according to their attributes and select the one with the highest probability. The process is explained by Utility Maximizing Model. To full fill the assumptions of Utility Maximizing Model (the free choice, the finite alternatives, and the irrelevant alternatives) discussed in Chapter 2, two assumptions are taken for the proposed model.

The first assumption is that the highest probability searching process can be interpreted by a sorting process supported by a set of paired comparisons between any two cues, which is similar to the sorting algorithms in the computer programming. As revealed in the observation experiment, there are six cue pair types: D-D, E-E, S-S, D-E, D-S, and E-S. If a preference prediction function can be built for each of them to predict the evacuees’ choice on any two cues, then the proposed model is able to compare all the cues in the cue pool to find out the cue with the highest probability. With such an assumption, the infinite combinations of any kind of possible cues in the cue pool are transformed into a finite sequence of paired comparisons. Moreover, the potential problem of the relevant alternatives in the cue pool is also avoided by the six kinds of cue pair comparisons. When the simulated evacuee does the comparison on any two cues, he has to choose the right one of the six preference prediction functions according to the cue pair type. Such a pre-process ensures that there is no relevant alternative in the following paired comparison on any two cues.

The second assumption is that the impact of the geometric attributes of the local architectural cue on the preference is continuous, which means that there will not be a sudden change in the choice on a cue pair when the geometric attribute changes in minors. Such an assumption can be supported by the accuracy of the human perception on distance and angle discussed in Chapter 2. With this assumption, the geometric attribute value is divided into several levels within a practical design value range. If the parameters of the preference prediction function can be measured for these levels, the proposed model can use the interpolation method to enable the preference prediction function to work with any specific geometric attribute value within this range. Meanwhile, these defined levels lead to a set of finite alternatives, which is necessary for the measurement experiment in the following.

With the both assumptions, the preference prediction function can be built for the six cue pair types

working within certain value ranges to enable the simulated evacuee to sort any number of cues in the cue pool to find the cue with the highest probability leading to the safety. In fact, as it is concluded in the end of the observation experiment, most of the evacuees choose Exit or Up Stair rather than Doorway Entrance. Thus, only the preference prediction function for the rest four cue pair types is needed. These cue pair types are: Doorway Entrance and Doorway Entrance (D-D), Exit and Exit (E-E), Up Stair and Up Stair (S-S), Up Stair and Exit (S-E). How to build these functions is the crucial part of the modeling work, which will be introduced in the next Section.

2) Setting the Goal of Next Step

After the simulated evacuee selects a cue with the highest probability leading to the safety, he will take the related actions of this cue (Table 3.3-14). Generally, a position of the cue will be set as the goal of next moving step. For Doorway Entrance, the mid point of the entrance will be set as the goal. For Up Stair, the mid point of the linkage edge between the current floor and the ramp of the stair will be set as the goal. For Exit, the mid point of the green rectangular will be set as the goal.

After the simulated evacuee selects the cue and set it as the goal of next moving step, he will plan a route to approach it in the next phase.

3.4.6 “Move”

In this phase, the simulated evacuee plans a route to the goal decided in the previous phase and moves one step distance toward it. In the proposed model, the Dijkstra’s algorithm is used to calculate the shortest route from the current position to the goal avoiding any obstacle in between. Although the whole route is calculated, only one step is implemented. After the movement, the simulated evacuee will face the move direction and check the arrival cues in the next phase.

3.4.7 Summary

The computational model framework of the route searching process is developed from the conceptual evacuation process model “Cue-Choice” in the literature studies. Moreover, some new features based on the previous questionnaire survey and the observation experiment are added. They are: the artificial vision, the memory mechanisms, the turning back action, and the related actions of the three local architectural cues. The crucial part of this model is the preference prediction function in the Choosing phase, which is introduced in the following.

3.5 Estimation of the Preference Prediction Function

To answer the fourth question in the end of Chapter 2, the suggested research method is used to transit the qualitative conclusions on the four information sources offering local architectural cues to the quantitative variables driving the computational model through the preference prediction function. In fact, as it is concluded at the end of the observation experiment, most of the evacuees choose Exit or Up Stair rather than Doorway Entrance. Thus, the CAVE-based Conjoint Analysis experiment in the following is focused on the remaining four kinds of cue pairs. They are: Doorway Entrance and Doorway Entrance (D-D), Exit and Exit (E-E), Up Stair and Up Stair (S-S), Up Stair and Exit (S-E).

3.5.1 Overview

During October 1st-7th 2007, 187 students (83 males and 104 females with the average age at 20, SD=0.9) from College of Architecture and Urban Planning, Tongji University, Shanghai, China participate in this experiment.

3.5.2 Design of the Estimation Experiment

According to the Conjoint Analysis approach, the estimation experiment is designed with several steps. First, the attributes of the local architectural cues influencing the participants' choice are deduced. Second, a hypothetic equation is composed for the preference prediction function supported by these attributes. Third, the levels of the variables in the function are defined. Fourth, the profiles (the virtual scenarios with paired cues) are prepared according to the level definitions. Finally, the interactive interface of the experiment in the CAVE platform is designed, through which the profiles will be presented to the participants and their responses will be collected for the further parameter estimation of the preference prediction function.

1) Attributes of the Local Architectural Cues

In order to build the preference prediction function, first seven attributes shared by the three local architectural cues are deduced, which are probably able to influence the evacuees' choice. According to the assumption of the paired cue comparisons in the model framework, a cue must have the attribute indicating which side, on the left or right, it is to the other cue in the pair. Meanwhile, according to the literature studies in Chapter 2, there are four kinds of information sources offering the local architectural cues. They are: the type of the architectural element in the circulation system, the feature of distance from the architectural elements to the individual, the feature of the scale of the architectural element, the feature of the angular positions of the architectural elements. In fact, the scale of the architectural element can be interpreted as the width feature and the height feature of the architectural element. Moreover, the angular positions of the architectural elements can be interpreted as two kinds of angular attributes. One is the angle between the view direction and the element position in the view. The other is the angle between the view direction and the axis of the element. Thus, it is deduced that the seven shared attributes of the three local architectural cues are as the following. The last five attributes are also illustrated for the three local architectural cues (Fig.3.5-1 ~ Fig.3.5-3).

Architectural Cue Model in Evacuation Simulation for Underground Space Design

1. The side of the cue in the pair, defined as **Side**.
2. The type of the cue, defined as **Type**;
3. The distance from the cue to the observation point, defined as **D**;
4. The width of the cue, defined as **W**;
5. The height of the cue, defined as **H**;
6. The angle between the direction of the view direction and the cue in the view, defined as **A1**;
7. The angle between the direction of the view direction and the cue axis, defined as **A2**;

The two angular attributes are defined in an egoistic coordination system with the center at the evacuee, which means the view direction of the evacuee is zero degree. Turning left gets positive degree and turning right gets negative degree.

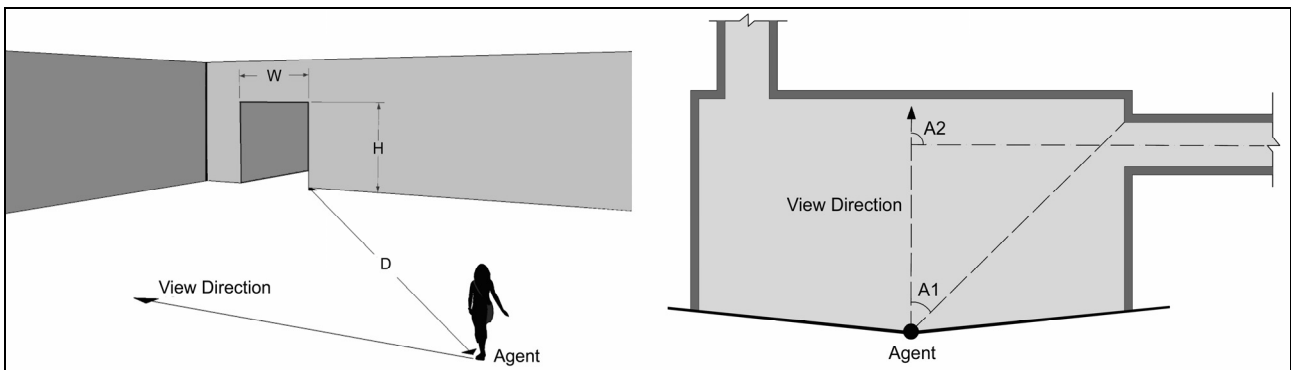


Figure 3.5-1 Attributes A1, A2, D, W, and H of Doorway Entrance

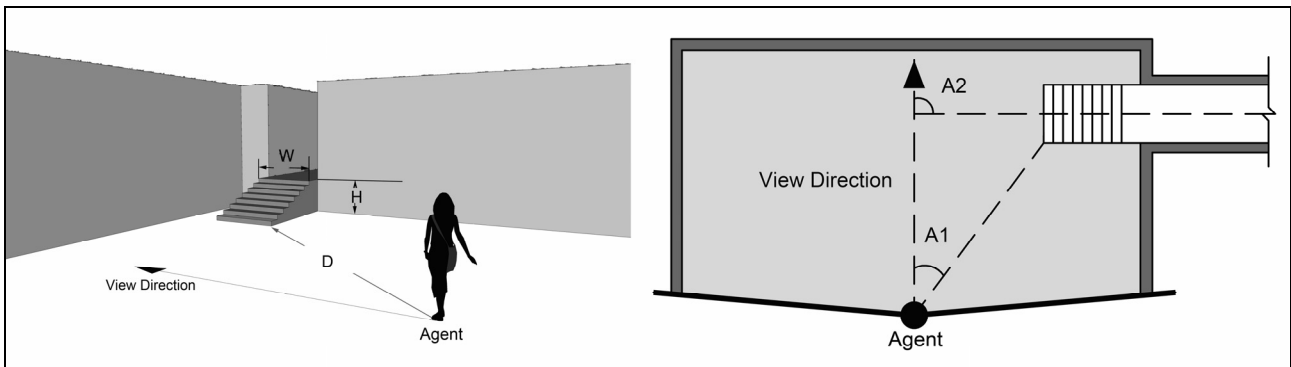


Figure 3.5-2 Attributes A1, A2, D, W, and H of Up Stair

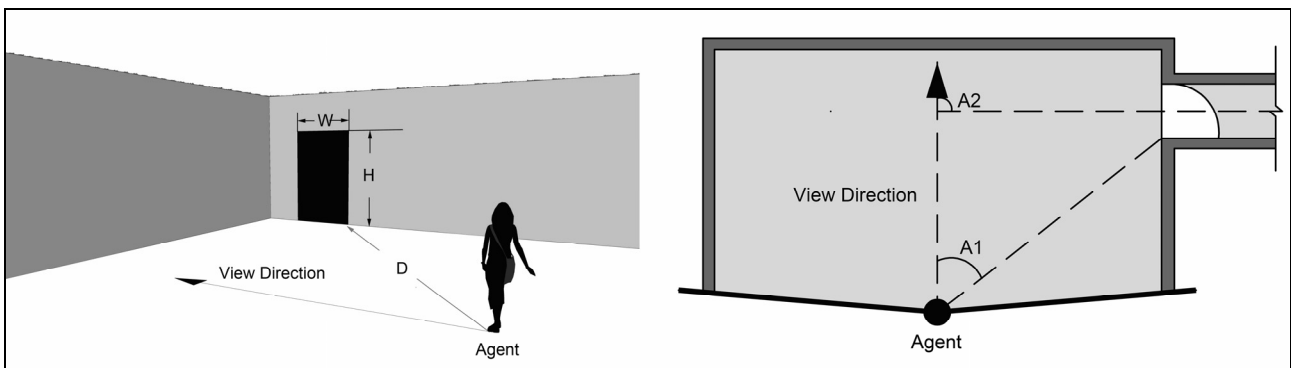


Figure 3.5-3 Attributes A1, A2, D, W, and H of Exit

2) Hypothetic Preference Prediction Function

According to the above attributes and the Conjoint Analysis approach suggested in Chapter 2, the variables and the equation is defined for the preference prediction function (Eq.2) to calculate the probability of the left cue being chosen in any cue pair type. According to the cue pair type and the levels of the variables, a specific set of the B values will be used in the calculation. These B values are the objects to estimate in this experiment.

The seven attributes function differently in the equation. The attribute Side defines that the probability is only predicted for the left cue being chosen in a cue pair. The attribute Type defines which set of B values is used in the calculation for a specific cue pair type. The remaining five attributes A1, A2, D, W, and H define the five dummy variable values and the B values from the set for a given cue pair. According to the spatial perception researches (Ashihara, 1970; Holl, Pallasmaa, & Perez-Gomez, 1994; Lawson, 2001), human beings are good at the relative comparison rather than the absolute perceptions. Thus, the ratio of every attribute's left value to right value in a pair is used as the variable indeed.

$$p(c_{left}) = \frac{e^{z_{picked}}}{e^{z_{picked}} + e^{z_{unpicked}}} \quad (2)$$

Where:

$p(c_{left})$ is the probability of left cue being chosen in the cue pair;

$$z_{picked} = \beta_0 + \beta_{RatioA1} X_{RatioA1} + \beta_{RatioA2} X_{RatioA2} + \beta_{RatioD} X_{RatioD} + \beta_{RatioW} X_{RatioW} + \beta_{RatioH} X_{RatioH}$$

$z_{unpicked} = 0$ (The reference alternative in the choice set.)

β_0 is the B value of the intercept.

β_i is the B value of a specific variable level.

X_i is the dummy variable for the RatioA1, RatioA2, RatioD, RatioW, and RatioH. When the reference level of the variable is input, the dummy variable will be 0. With other levels, it is 1.

3) Levels of the Variables

With the hypothetic function, all the levels of the variables are defined. As revealed in the previous research (Sun et al., 2007), the change of B value is nonlinear when the variable value (the attribute ratio) changes in a linear way, which means that this research has to estimate the B values for as many levels as possible for every variable. A level distribution with higher density and larger range can lead to a better performance of the preference prediction function. In the following, the ranges of the attribute values are first defined for the experiment. Then, within these ranges, the number of levels and the encoding plans from the levels to the geometric values of the two cues in any virtual scene are defined.

First, according to human vision specifications in Chapter 2, the limitations of the CAVE platform (Appendix C) and the building codes of the public underground space design in China (Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2003), the value ranges of the five attributes (Table 3.5-1) are defined for the experiment.

Table 3.5-1 Value ranges of the five attributes

| | A1 (degree) | | A2 (degree) | | D (meter) | | W (meter) | | H (meter) | |
|-------------------------|------------------------|------|------------------------|------|----------------------|------|----------------------|------|----------------------|------|
| | Min. | Max. | Min. | Max. | Min. | Max. | Min. | Max. | Min. | Max. |
| Doorway Entrance | -90 | +90 | -90 | +90 | 5 | 40 | 3 | 24 | 2.5 | 7.5 |
| Exit | -90 | +90 | -90 | +90 | 5 | 40 | 1 | 8 | 2.1 | 6.3 |
| Up Stair | -90 | +90 | -180 | +180 | 5 | 40 | 0.9 | 7.2 | 2.1 | 6.3 |

Next, the number of the levels is defined according to the capacity of the experiment. To keep the participant absorbed in the experiment and with a positive mood, the time period of making choices is planned within around 5 minutes for every participant. It is assumed that a rapid choice driven by instinct needs around 2 second. With such an assumption and 1-second interval after every choice, one participant can make around one hundred choices during 5 minutes. With the applications from 205 volunteers, the capacity of the experiment is around 20,000 choices. In other words, one of the four cue pair types can have around 5,000 choices. If the estimation needs around 100 choices for every profile (a scene with a specific cue pair), the number of the profiles for one cue pair type is around 50. According to the Fractional Factorial Design technique (Montgomery, 1991), the number of the levels and the profiles for the four cue pair types are generated (Table 3.5-2). Most of the variables have 7 levels to keep the number of the profiles within 50, except the variable RatioA2 in scene set S-E, which has 2 more levels for the big difference between the value ranges of Up Stair and Exit (Table 3.5-1).

Table 3.5-2 Number of the levels and the scenes for every cue pair type

| Scene Type | Levels of the Variables | | | | | | Number of Scenes |
|-------------------|--------------------------------|----------------|----------------|---------------|---------------|---------------|-------------------------|
| | Side | RatioA1 | RatioA2 | RatioD | RatioH | RatioW | |
| D-D | | 7 | 7 | 7 | 5 | 7 | 49 |
| S-S | | 7 | 7 | 7 | 5 | 7 | 49 |
| E-E | | 7 | 7 | 7 | 5 | 7 | 49 |
| S-E | 2 | 7 | 9 | 7 | 5 | 7 | 81 |

Last, the encoding plans for the four cue pair types are defined (Table 3.5-3 ~ Table 3.5-6). The variable levels are mapped to the ratios. As examples of the ratio, the practical values within the ranges (Table 3.5-1) are listed, which are used in the design of the virtual scenarios. Notably, the levels in the encoding plan S-E are ratios of the Up Stair’s value to the Exit’s value. If the ratios of the left cue’s value to the right cue’s value are used as in the other encoding plans, the number of RatioA2 and RatioW’s levels has to be doubled to cover all the possible ratios. To avoid it this special encoding plan is used. Furthermore, this encoding plan includes one more variable Side to indicate on which side the Up Stair is in the Stair-Exit pair.

Table 3.5-3 Encoding plan of the Scene D-D for experiment design and data analysis

| D-D Scene | | RatioA1 (L : R) | RatioD (L : R) | RatioH (L : R) | RatioA2 (L : R) | RatioW (L : R) | |
|------------------|--------------|----------------------------|---------------------------|---------------------------|----------------------------|---------------------------|--------------------|
| Level | 1 | Mapped Value | 1 : 8 | 1 : 8 | 1 : 3 | 1 : 16 | 1 : 8 |
| | | Scene Value | 7.5 : 60 | 5 : 40 | 2.5 : 7.5 | 5 : 80 | 3 : 24 |
| | 2 | Mapped Value | 1 : 4 | 1 : 4 | 1 : 2 | 1 : 8 | 1 : 4 |
| | | Scene Value | 7.5 : 30 15 : 60 | 5 : 20 10 : 40 | 2.5 : 5.0 | 5 : 40 | 3 : 12 6 : 24 |
| | 3 | Mapped Value | 1 : 2 | 1 : 2 | 1 : 1 | 1 : 4 | 1 : 2 |
| | | Scene Value | 7.5 : 15 | 5 : 10 | 2.5 : 2.5 | 5 : 20 20 : 80 | 3 : 6 |
| | | | 15 : 30 30 : 60 | 10 : 20 20 : 40 | 5.0 : 5.0 7.5 : 7.5 | | 6 : 12 12 : 24 |
| | 4 | Mapped Value | 1 : 1 | 1 : 1 | 2 : 1 | 1 : 1 | 1 : 1 |
| | | Scene Value | 7.5 : 7.5 | 5 : 5 | 5.0 : 2.5 | 5 : 5 | 3 : 3 |
| | | | 15 : 15 | 10 : 10 | | 20 : 20 | 6 : 6 |
| | | | 30 : 30 60 : 60 | 20 : 20 40 : 40 | | 40 : 40 80 : 80 | 12 : 12 24 : 24 |
| | 5 | Mapped Value | 2 : 1 | 2 : 1 | 3 : 1 | 4 : 1 | 2 : 1 |
| | | Scene Value | 15 : 7.5 | 10 : 5 | 7.5 : 2.5 | 20 : 5 | 6 : 3 |
| | | | 30 : 15 60 : 30 | 20 : 10 40 : 20 | | 80 : 20 | 12 : 6 24 : 12 |
| 6 | Mapped Value | 4 : 1 | 4 : 1 | | 8 : 1 | 4 : 1 | |
| | Scene Value | 30 : 7.5 60 : 15 | 20 : 5 40 : 10 | | 40 : 5 | 12 : 3 24 : 6 | |
| 7 | Mapped Value | 8 : 1 | 8 : 1 | | 16 : 1 | 8 : 1 | |
| | Scene Value | 60 : 7.5 | 40 : 5 | | 80 : 5 | 24 : 3 | |

Notes: **L**: left cue; **R**: right cue

Architectural Cue Model in Evacuation Simulation for Underground Space Design

Table 3.5-4 Encoding plan of the Scene E-E for experiment design and data analysis

| E-E Scene | | RatioA1 (L : R) | RatioD (L : R) | RatioH (L : R) | RatioA2 (L : R) | RatioW (L : R) | | | |
|------------------|-------------|----------------------------|--------------------------------------------|----------------------------------------|-------------------------------------|----------------------------------------|----------------------------------|-------------------|-------------------------|
| Level | 1 | Mapped Value | 1 : 8 | 1 : 8 | 1 : 3 | 1 : 16 | 1 : 8 | | |
| | | Scene Value | 7.5 : 60 | 5 : 40 | 2.5 : 6.3 | 5 : 80 | 1 : 8 | | |
| | 2 | Mapped Value | 1 : 4 | 1 : 4 | 1 : 2 | 1 : 8 | 1 : 4 | | |
| | | Scene Value | 7.5 : 30 15 : 60 | 5 : 20 10 : 40 | 2.1 : 4.2 | 5 : 40 | 1 : 4 2 : 8 | | |
| | 3 | Mapped Value | 1 : 2 | 1 : 2 | 1 : 1 | 1 : 4 | 1 : 2 | | |
| | | Scene Value | 7.5 : 15 15 : 30 30 : 60 | 5 : 10 10 : 20 20 : 40 | 2.1 : 2.1 4.2 : 4.2 6.3 : 6.3 | 5 : 20 20 : 80 | 1 : 2 2 : 4 4 : 8 | | |
| | | | Mapped Value | 1 : 1 | 1 : 1 | 2 : 1 | 1 : 1 | 1 : 1 | |
| | 4 | Scene Value | 7.5 : 7.5 15 : 15 30 : 30 60 : 60 | 5 : 5 10 : 10 20 : 20 40 : 40 | 4.2 : 2.1 | 5 : 5 20 : 20 40 : 40 80 : 80 | 1 : 1 2 : 2 4 : 4 8 : 8 | | |
| | | | 5 | Mapped Value | 2 : 1 | 2 : 1 | 3 : 1 | 4 : 1 | 2 : 1 |
| | | | | Scene Value | 15 : 7.5 30 : 15 60 : 30 | 10 : 5 20 : 10 40 : 20 | 6.3 : 2.1 | 20 : 5 80 : 20 | 2 : 1 4 : 2 8 : 4 |
| | | | 6 | Mapped Value | 4 : 1 | 4 : 1 | | 8 : 1 | 4 : 1 |
| | Scene Value | 30 : 7.5 60 : 15 | | 20 : 5 40 : 10 | | 40 : 5 | 4 : 1 8 : 2 | | |
| | 7 | Mapped Value | 8 : 1 | 8 : 1 | | 16 : 1 | 8 : 1 | | |
| | | Scene Value | 60 : 7.5 | 40 : 5 | | 80 : 5 | 8 : 1 | | |

Notes: **L**: left cue; **R**: right cue

Table 3.5-5 Encoding plan of the Scene S-S for experiment design and data analysis

| S-S Scene | | RatioA1 (L : R) | RatioD (L : R) | RatioH (L : R) | RatioA2 (L : R) | RatioW (L : R) | | | |
|------------------|-------------|---------------------|--------------------------------------------|----------------------------------------|-------------------------------------|--------------------------------------------|--------------------------------------------------|---------------------|-------------------------------------|
| Level | 1 | Mapped Value | 1 : 8 | 1 : 8 | 1 : 3 | 1 : 16 | 1 : 8 | | |
| | | Scene Value | 7.5 : 60 | 5 : 40 | 2.1 : 6.3 | 10 : 160 | 0.9 : 7.2 | | |
| | 2 | Mapped Value | 1 : 4 | 1 : 4 | 1 : 2 | 1 : 8 | 1 : 4 | | |
| | | Scene Value | 7.5 : 30 15 : 60 | 5 : 20 10 : 40 | 2.1 : 4.2 | 10 : 80 | 0.9 : 3.6 1.8 : 7.2 | | |
| | 3 | Mapped Value | 1 : 2 | 1 : 2 | 1 : 1 | 1 : 4 | 1 : 2 | | |
| | | Scene Value | 7.5 : 15 15 : 30 30 : 60 | 5 : 10 10 : 20 20 : 40 | 2.1 : 2.1 4.2 : 4.2 6.3 : 6.3 | 10 : 40 40 : 160 | 0.9 : 1.8 1.8 : 3.6 3.6 : 7.2 | | |
| | | | Mapped Value | 1 : 1 | 1 : 1 | 2 : 1 | 1 : 1 | 1 : 1 | |
| | 4 | Scene Value | 7.5 : 7.5 15 : 15 30 : 30 60 : 60 | 5 : 5 10 : 10 20 : 20 40 : 40 | 4.2 : 2.1 | 10 : 10 40 : 40 80 : 80 160 : 160 | 0.9 : 0.9 1.8 : 1.8 3.6 : 3.6 7.2 : 7.2 | | |
| | | | 5 | Mapped Value | 2 : 1 | 2 : 1 | 3 : 1 | 4 : 1 | 2 : 1 |
| | | | | Scene Value | 15 : 7.5 30 : 15 60 : 30 | 10 : 5 20 : 10 40 : 20 | 6.3 : 2.1 | 40 : 10 160 : 40 | 1.8 : 0.9 3.6 : 1.8 7.2 : 3.6 |
| | | | 6 | | Mapped Value | 4 : 1 | 4 : 1 | | 8 : 1 |
| | Scene Value | 30 : 7.5 60 : 15 | | 20 : 5 40 : 10 | | 80 : 10 | 3.6 : 0.9 7.2 : 1.8 | | |
| | | 7 | Mapped Value | 8 : 1 | 8 : 1 | | 16 : 1 | 8 : 1 | |
| | Scene Value | | 60 : 7.5 | 40 : 5 | | 160 : 10 | 7.2 : 0.9 | | |

Notes: **L**: left cue; **R**: right cue

Architectural Cue Model in Evacuation Simulation for Underground Space Design

Table 3.5-6 Encoding plan of the Scene S-E for experiment design

| S-E Scene | | RatioA1 (S : E) | RatioD (S : E) | RatioH (S : E) | RatioA2 (S : E) | RatioW (S : E) | Stair Side | |
|------------------|--------------|--------------------|--------------------------------------------|----------------------------------------|-------------------------------------|------------------------------------------|------------------------------------------|-------------------|
| Level | 1 | Mapped Value | 1 : 8 | 1 : 8 | 1 : 3 | 1 : 8 | 0.1125 : 1 | Left |
| | | Scene Value | 7.5 : 60 | 5 : 40 | 2.1 : 6.3 | 10 : 80 | 0.9 : 8 | Stair is on left |
| | 2 | Mapped Value | 1 : 4 | 1 : 4 | 1 : 2 | 1 : 4 | 0.225 : 1 | Right |
| | | Scene Value | 7.5 : 30 15 : 60 | 5 : 20 10 : 40 | 2.1 : 4.2 | 10 : 40 | 0.9 : 4 1.8 : 8 | Stair is on right |
| | 3 | Mapped Value | 1 : 2 | 1 : 2 | 1 : 1 | 1 : 2 | 0.45 : 1 | |
| | | Scene Value | 7.5 : 15 15 : 30 30 : 60 | 5 : 10 10 : 20 20 : 40 | 2.1 : 2.1 4.2 : 4.2 6.3 : 6.3 | 10 : 20 40 : 80 | 0.9 : 2 1.8 : 4 3.6 : 8 | |
| | | | | | | | | |
| | 4 | Mapped Value | 1 : 1 | 1 : 1 | 2 : 1 | 1 : 1 | 0.9 : 1 | |
| | | Scene Value | 7.5 : 7.5 15 : 15 30 : 30 60 : 60 | 5 : 5 10 : 10 20 : 20 40 : 40 | 4.2 : 2.1 | 40 : 40 80 : 80 | 0.9 : 1 1.8 : 2 3.6 : 4 7.2 : 8 | |
| | | | | | | | | |
| | | | | | | | | |
| | 5 | Mapped Value | 2 : 1 | 2 : 1 | 3 : 1 | 2 : 1 | 1.8 : 1 | |
| | | Scene Value | 15 : 7.5 30 : 15 60 : 30 | 10 : 5 20 : 10 40 : 20 | 6.3 : 2.1 | 10 : 5 40 : 20 80 : 40 160 : 80 | 1.8 : 1 3.6 : 2 7.2 : 4 | |
| | | | | | | | | |
| | | | | | | | | |
| | 6 | Mapped Value | 4 : 1 | 4 : 1 | | 4 : 1 | 3.6 : 1 | |
| | | Scene Value | 30 : 7.5 60 : 15 | 20 : 5 40 : 10 | | 80 : 20 160 : 40 | 3.6 : 1 7.2 : 2 | |
| | 7 | Mapped Value | 8 : 1 | 8 : 1 | | 8 : 1 | 7.2 : 1 | |
| Scene Value | | 60 : 7.5 | 40 : 5 | | 40 : 5 160 : 20 | 7.2 : 1 | | |
| 8 | Mapped Value | | | | 16 : 1 | | | |
| | Scene Value | | | | 80 : 5 | | | |
| 9 | Mapped Value | | | | 32 : 1 | | | |
| | Scene Value | | | | 160 : 5 | | | |

Notes: **S**: Stair; **E**: Exit

4) Virtual Scenario Design with Paired Cues

With the generated profiles for every cue pair type (Table 3.5-2), all virtual scenarios are designed according to the practical values related to the levels in the profile. This design process includes three phases.

In the first phase, the levels are mapped into the ratios according to the encoding plans (Table 3.5-3 ~ Table 3.5-6). For example, the generated profile of Scene No. 39 including six variables with a set of specific levels (Table 3.5-7) is mapped into five ratios and one side definition (Table 3.5-8). For the other three cue pair types, the process is similar except that there is no variable called Stair Side.

Table 3.5-7 Profile of Scene No.39 in Stair-Exit set

| ID | Levels | | | | | Stair Side |
|----|---------|--------|--------|---------|--------|------------|
| | RatioA1 | RatioD | RatioH | RatioA2 | RatioW | |
| 39 | 1 | 5 | 4 | 7 | 7 | 2 |

Table 3.5-8 Mapped values of Scene No.39 in Stair-Exit set

| ID | Values | | | | | Stair Side |
|----|---------|--------|--------|---------|---------|------------|
| | RatioA1 | RatioD | RatioH | RatioA2 | RatioW | |
| 39 | 1 : 8 | 2 : 1 | 2 : 1 | 8 : 1 | 7.2 : 1 | Right |

In the second phase, the practical geometric values related to the ratios are selected to depict the two cues in one scene according to the encoding plans (Table 3.5-3 ~ Table 3.5-6). For example, the two cues of the scene No.39 in Stair-Exit set are depicted with the selected the geometric values (Table 3.5-9). For all the profiles, the process is the same.

Table 3.5-9 Depiction of the two cues of Scene No.39 in Stair-Exit set

| ID | Side | Type | A1 (degree) | D (meter) | H (meter) | A2 (degree) | W (meter) |
|----|-----------|-------|----------------|--------------|--------------|----------------|--------------|
| 39 | Left Cue | Exit | 60 | 10 | 2.1 | 5 | 1 |
| | Right Cue | Stair | 7.5 | 20 | 4.2 | 40 | 7.2 |

In the last phase, the depictions are transformed into static virtual scenarios. For example, the depiction of the scene No. 39 in Stair-Exit set (Table 3.5-9) is transformed into a virtual scenario (Fig.3.5-4).

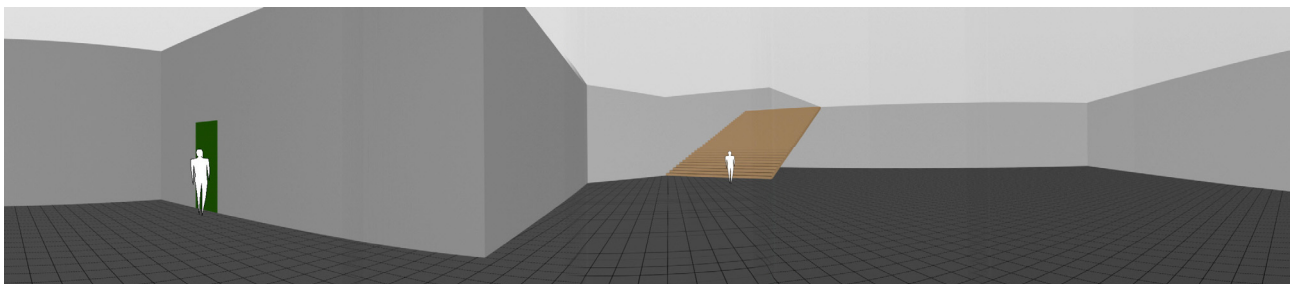


Figure 3.5-4 Distorted human view of the scene No.39 in Stair-Exit set

With all the attributes of the both cues designated, only the space with its ceiling and walls to hold

the cues needs to be designed. For the space holding Exit or Up Stair, the height is set to 4.2 or 6.3 meters to match the normal space or the big space like the hall in the underground. For the space holding Doorway Entrance, the height is set to 5 or 7.5 meters. The space walls are designed according to three rules. First, every piece of wall has to be parallel or perpendicular to the axis of one cue. Next, the walls should confine the space with the size just holding the two cues. Last, except the walls inside the Doorway Entrance there should not be any piece of wall invisible to the observation point, which means no wall can be laid along the eye sight or at the back of some other walls.

Besides the design of the space, the virtual scenario is also designed according to the visual cues mentioned in the end of Chapter 2. The scenario is rendered according to the perspective principle to provide the visual cue of Overlay and Linear Perspective. The participant can find Doorway Entrance by the different Shade of the wall. The participant's observing height is fixed at 1.75 meter above the floor by the Height Adjustor to support the visual cue of Height in Visual Field. The participant can always see the square pavement on the floor to have the visual cue of Size. Additionally, two human profiles are put in front of each cue to provide the both the cue of Height in Visual Field and the cue of Size, which can lead to the depth perception. All these visual cues can improve the evacuee's spatial perception.

Furthermore, the virtual scenario is presented in a very abstract way validated in the observation experiment, which only offers the three-dimensional geometric features of the local architectural cues. Exit is a symbolic rectangular in green, Up Stair is a symbolic sets of steps in brown, and Doorway Entrance can be distinguished through perspective and different shade. There is no non-geometric difference between any two cues in the same type. All the other cues, such as signs, moving people, growing smoke, are avoided in the scenario.

Finally, 228 static virtual scenarios are prepared for the estimation experiment, with which all the sets of B values relating to the levels can be estimated as the parameters to support the hypothetic preference prediction function.

5) Interactive Interface Design

After the static virtual scenarios are read, the interactive interface is designed for the experiment in the CAVE platform (Fig.3.5-5). A program developed in Visual Basic is used to control the interactive interface, which can provide the static virtual scenarios, respond to the participant's input and record his choices in a data file, which can be read by SPSS.

The virtual scenarios are presented on the screen of the CAVE platform with other stimulations. To impose the psychological pressure to the participants, a noisy sound mixed by the alarm and the heart beating can always be heard by the participants through the ear phone during the whole experiment. Moreover, they can notice a clock on the screen indicating the time used in every scenario during their decision making, with which they are urged to make decisions on the cue pair according to their instinct very rapidly.

The operation to make a choice in a scenario is very similar to the navigation in the observation experiment. To avoid the operational preferences of the mouse or the arrow keys controlled by one hand, the participants are asked to use the both hands, the left hand controlling key Z to choose the cue on the left side and the right hand controlling key M to choose the cue on the right side. After the participant chooses one cue, the program will switch to an interval black screen with the

stepping sound to let the participant relax for 1 second. Then a new scenario will be presented.

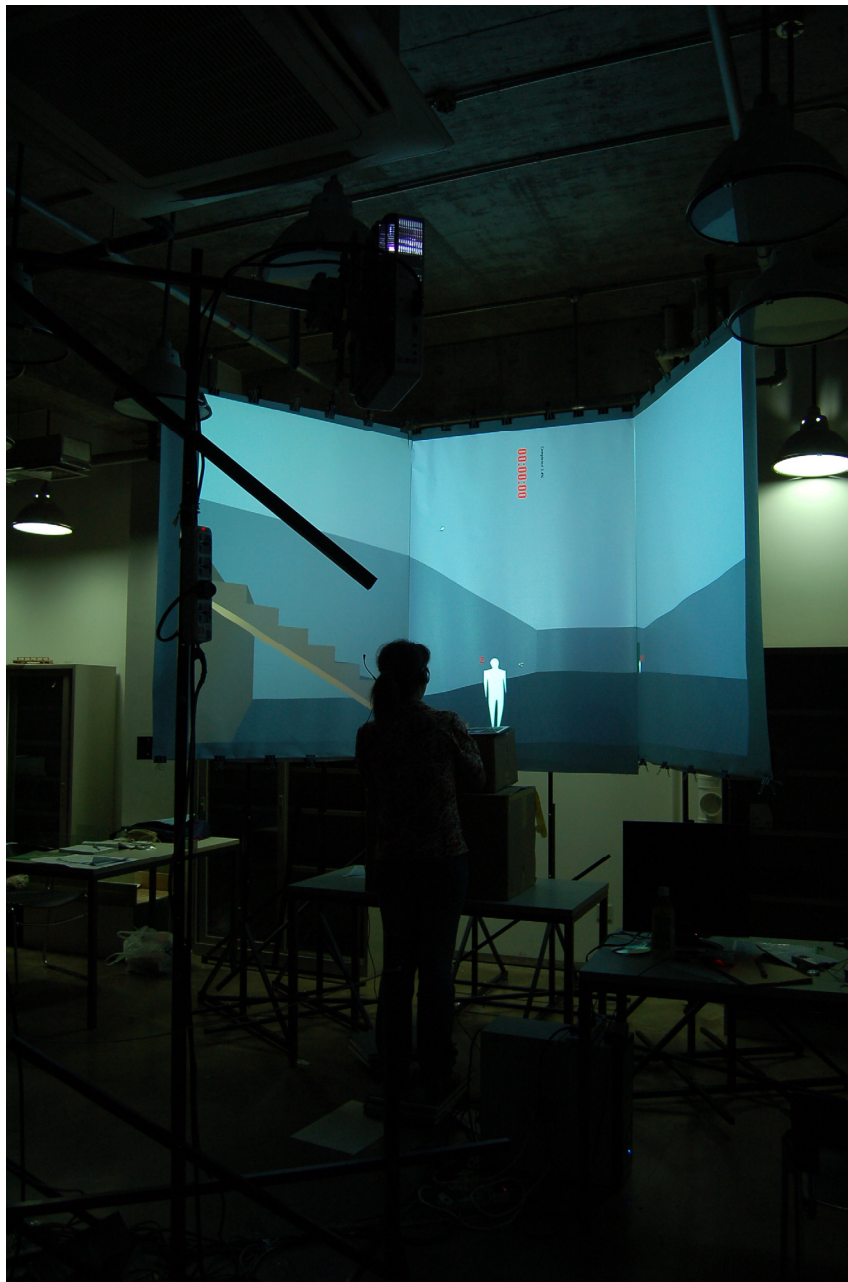


Figure 3.5-5 Interactive interface for the experiment

The participants' choices are recorded by the program automatically. One choice is recorded into one row stands for the participant's decision on the left cue, which includes the column Chosen and other five columns corresponding to the five variables. If the left cue is being chosen, the column Chosen is set to 1. If it is not chosen, in other words the right cue is chosen, the column Chosen is set to 0. The other five columns are filled with the levels mapped reversely from the scenario depiction according to the encoding plans (Table 3.5-3 ~ Table 3.5-6). Notably, the reverse mapping process of Stair-Exit scenarios uses a new encoding plan (Table 3.5-10) different from the original plan used in the scene generation. With this new plan, the numbers of RatioA2 and RatioW's levels are doubled. When the left cue is Stair, the levels are mapped from 1 to 9 for RatioA2 and from 1 to 7 for RatioW. When the left cue is Exit, the levels are mapped from 10 to 18 for RatioA2 and from 8 to 14 for RatioW. For example, if a participant chooses the right cue in the scene No.39 depicted in Table 3.5-9, such a choice will be recorded into one row (Table 3.5-11).

Table 3.5-10 Encoding plan of the Scene S-E for data analysis

| S-E Scene | RatioA1 (L : R) | RatioD (L : R) | RatioH (L : R) | RatioA2 (L : R) | | RatioW (L : R) | |
|-----------|-----------------|----------------|----------------|-----------------|--------------|----------------|--------------|
| | | | | Stair on Left | Exit on Left | Stair on Left | Exit on Left |
| Level | 1 | 1 : 8 | 1 : 8 | 1 : 3 | 1 : 8 | | 0.1125 : 1 |
| | 2 | 1 : 4 | 1 : 4 | 1 : 2 | 1 : 4 | | 0.225 : 1 |
| | 3 | 1 : 2 | 1 : 2 | 1 : 1 | 1 : 2 | | 0.45 : 1 |
| | 4 | 1 : 1 | 1 : 1 | 2 : 1 | 1 : 1 | | 0.9 : 1 |
| | 5 | 2 : 1 | 2 : 1 | 3 : 1 | 2 : 1 | | 1.8 : 1 |
| | 6 | 4 : 1 | 4 : 1 | | 4 : 1 | | 3.6 : 1 |
| | 7 | 8 : 1 | 8 : 1 | | 8 : 1 | | 7.2 : 1 |
| | 8 | | | | 16 : 1 | | 1 : 7.2 |
| | 9 | | | | 32 : 1 | | 1 : 3.6 |
| | 10 | | | | | 1 : 32 | 1 : 1.8 |
| | 11 | | | | | 1 : 16 | 1 : 0.9 |
| | 12 | | | | | 1 : 8 | 1 : 0.45 |
| | 13 | | | | | 1 : 4 | 1 : 0.225 |
| | 14 | | | | | 1 : 2 | 1 : 0.1125 |
| | 15 | | | | | 1 : 1 | |
| | 16 | | | | | 2 : 1 | |
| | 17 | | | | | 4 : 1 | |
| | 18 | | | | | 8 : 1 | |

Notes: L: left cue; R: right cue

Table 3.5-11 Recorded choice of Scene No.39 in Stair-Exit set

| Chosen | RatioA1 | RatioD | RatioH | RatioA2 | RatioW |
|--------|---------|--------|--------|---------|--------|
| 0 | 7 | 3 | 2 | 12 | 8 |

3.5.3 Procedure

The volunteers are divided into two groups for the experiment. Some of the volunteers are absent in the reserved experiment time period. Finally 187 participants participate in the experiment. The first group of 96 participants implements 177 choices in the experiment of two scene sets (D-D with 49 choices and S-S with 49 choices) plus a control scene set S-D with 81 choices. The second group of 91 participants implements 130 choices in the experiment of another two scene sets (E-E with 49 choices and S-E with 81 choices). Additionally, they implement one more choice in a D-D scene, which is replaced by another D-D scene by mistake in the first experiment.

In both groups, after the experiment staff adjusts the participant’s eyes to the ideal observation position, the participant is asked to practice making choice in the CAVE platform first. During the practice, the Doorway Entrance, the symbolic Exit and Up Stair are learned. When he is ready for the experiment, he is asked to listen to a recorded direction, in which he is asked to imagine himself staying in an underground space. The fire alarm urges all the persons to evacuate as soon as possible. Most persons have evacuated successfully. It seems he or she is the only one in this space. He must choose a direction hinted by either of the two cues in every scene to evacuate toward the most likely safe place by his instinct. He can press Key Z to run toward the left cue or Key M toward the right cue. It is emphasized that all the scenes they see are separated and not related to each other in space.

All the participants in group one finish the 177-choices experiment in around 6 minutes. All the participants in group two finish the 130-choices experiment in around 4 minutes. The both time periods exclude the 2-minute preparation work and include 1-second-interval after every choice. Thus, the average decision making time is around 0.95 second.

After the experiment, 29,104 choices (D-D: 4,795 choices, E-E: 4,459 choices, S-S: 4,704 choices, S-E: 7,370 choices, and S-D: 7,776 choices) are collected with one choice in the Stair-Exit set missing.

Notably, a control scene set Stair-Doorway with 81 choices is added into the first group's task to check whether the static choices made by the participants are reliable referring to the conclusion in the dynamic observation experiment. The scene set is designed through the same process as the other scene sets. In the 7,776 collected choices, 80 % choices fall in the Up Stair side, no matter what the attributes of Up Stair and Doorway Entrance are. Such a result matches the conclusion that the most the evacuees prefer Up Stair rather than Doorway Entrance in the previous dynamic observation experiment. Thus, the choices collected in this experiment are regarded reliable.

3.5.4 Analysis

With all the choice data collected, the Multinomial Logistic Regression module in SPSS is used to estimate the B values of the hypothetic preference prediction function. According to the format of the recorded choice (Table 3.5-11), the column Chosen is designated as the Dependent and the other five columns as Factors. Within the two levels of the Dependent, the Reference Category is set to 0 (Not Chosen). A custom model is defined for the regression, in which the five factors are treated as Main Effects and processed in a Forward Stepwise way. According to the regression reports of the four cue pair types (Appendix F), the performance of the function, the seven attributes in the function, and the Ratio-Probability distributions of the five variables are analyzed.

1) Performance of the Function

To study the regression results at a macro level, the performance of the estimated function is analyzed. According to an overview on the model performance in the regression results (Table 3.5-12), it is noticed that the hypothetic function with the estimated parameters obviously has some prediction ability, and such an ability changes with the cue pair type reasonably.

First, it is noticed that all the Overall Predicted Correction Percentages of the estimated function (Table 3.5-12) are obviously higher than the average fifty percentage of a random choosing function, which means that the seven-attribute-based function reflects the subconscious rules of the participants' choosing behavior to a certain extent.

Next, it is noticed that the McFadden's R^2 and Overall Predicted Correction Percentage change with the different cue pair type (Table 3.5-12), which matches the assumption of Utility Maximizing Model introduced in Chapter 2. In such a model, the utilities are assumed to consist of a systematic measurable component and a random component because of the measurement errors and the taste variation. In other words, the choice behavior on the cue pairs is determined by both the subconscious rules shared by the participants and the individual's characteristic or random response. In fact, the trend of the varying performance is found reasonable, if the cue pair types are analyzed according to the hints they offer.

Architectural Cue Model in Evacuation Simulation for Underground Space Design

Doorway Entrance offers the hint that there might be some exits, stairs or other doorways behind it, but not for sure. Such a cue type has an indirect and weak relation to the safety. So the D-D choice has the most individual randomness among the four cue pair types. The prediction performance of such a pair is the lowest.

Exit should be the most direct and strongest cue type relating to “the safety” according to the building codes. A part of the participants choose it as the best choice. However, it is revealed that in the observation experiment a part of the participants share a negative impression on the exits because of the tons of reports on the death caused by the blocked exits in China. Thus, another part of the participants will not choose Exit when there is an Up Stair. As a result, there are two obviously opposite comprehensions of the cue type Exit, which leads to two propensities in making choice between Up Stair and Exit. Providing only one answer, the Overall Predicted Correction Percentage of S-E choice set with the bipolarity must indicate a relatively low performance. Anyway, because of the strong hint from either Exit or Up Stair, the performance is still better than D-D set.

Both the Up Stair and the Exit offers a strong hint to the safety. In S-S set and E-E set, the two cues in the pair have the same type. The choices are influenced by the different attributes relating to the variables. Thus, these two sets have the highest performances, which are close to each other.

Moreover, the varying performance matches the conclusion of the observation experiment, in which it is revealed that the evacuees making decisions with more Doorway Entrances has some weak preferences shared or much randomness, while the evacuees making decisions with more Exit and Up Stair has the strong preference shared and a little randomness. According to such a conclusion, the choice prediction of D-D set must be most difficult.

In summary, the hypothetic function with the estimated parameters has the prediction ability to a certain extent, which actually changes reasonably, when the function works on the different cue pair type.

Table 3.5-12 Performance of the function

| Cue Pair Type | McFadden's R² | Overall Predicted Correction Percentage |
|----------------------|---------------------------------|------------------------------------------------|
| D-D | 0.105 | 65.1% |
| S-E | 0.149 | 69.2% |
| S-S | 0.209 | 71.8% |
| E-E | 0.220 | 73.5% |

2) Seven Attributes

To study the regression results at a meso level, the seven attributes of the local architectural cues in the predicted function are analyzed. According to the B values in the regression reports (Appendix F), the polylines are generated to indicate the relationship between the logarithm of the variable values and the probabilities of the left cue being chosen (Fig.3.5-6 ~ Fig.3.5-9). In these figures, each polyline stands for one variable. The horizontal coordination value of a node on the polyline is the logarithm of the variable value (the ratio of the left cue's attribute value to the right cue's attribute value). Its vertical coordination value is the probability predicted by the hypothetic function when the variable represented by the polyline is set to the exponent of its horizontal coordination value and the rest variables are set to ratio 1:1. Notably, without the B value of the

exact ratio 1:1 for RatioW in S-E set, linear interpolation method is used. With these polylines, the seven attributes: Type, Side, A1, D, H, A2, and W are analyzed.

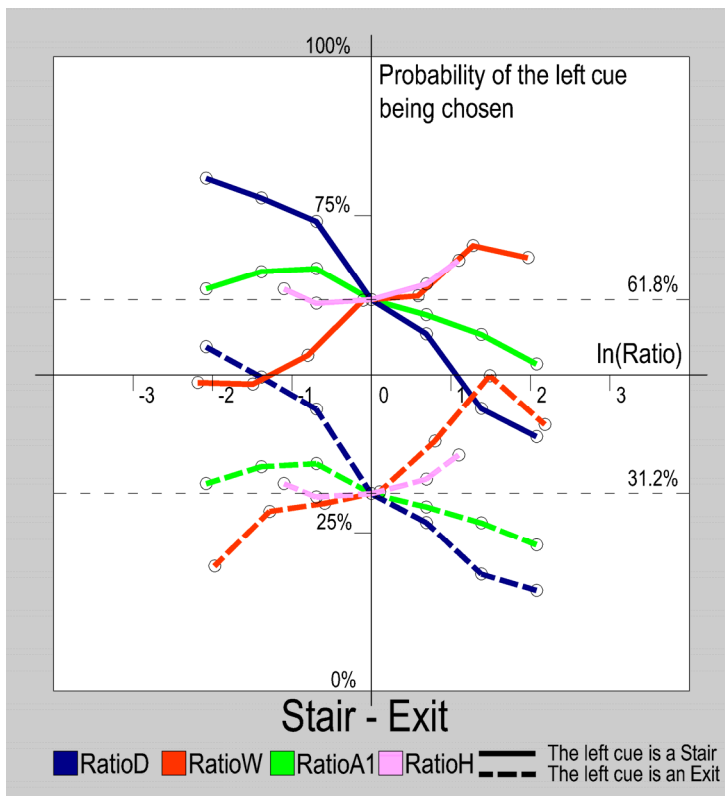


Figure 3.5-6 Relationship of the attributes and the probabilities in the S-E set

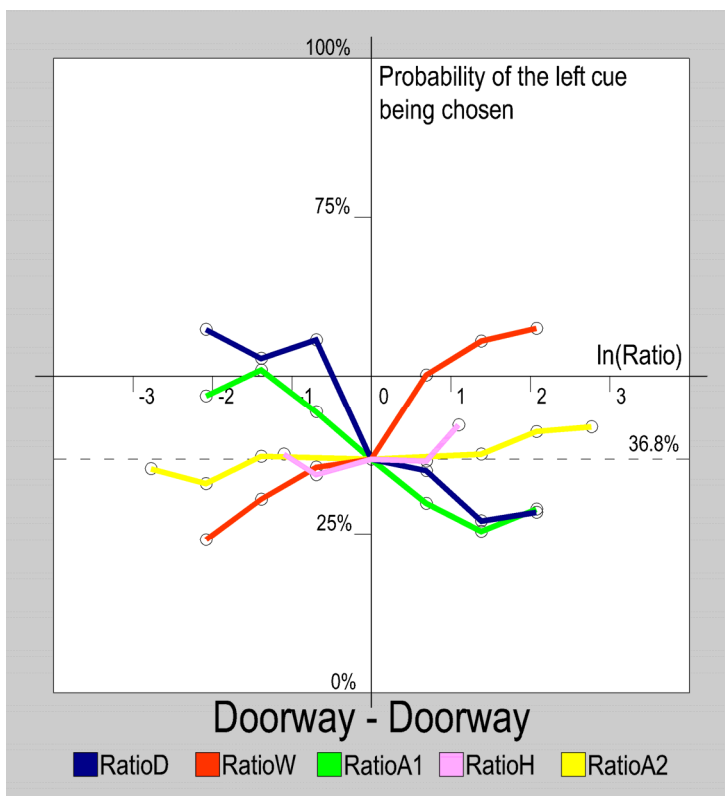


Figure 3.5-7 Relationship of the attributes and the probabilities in the D-D set

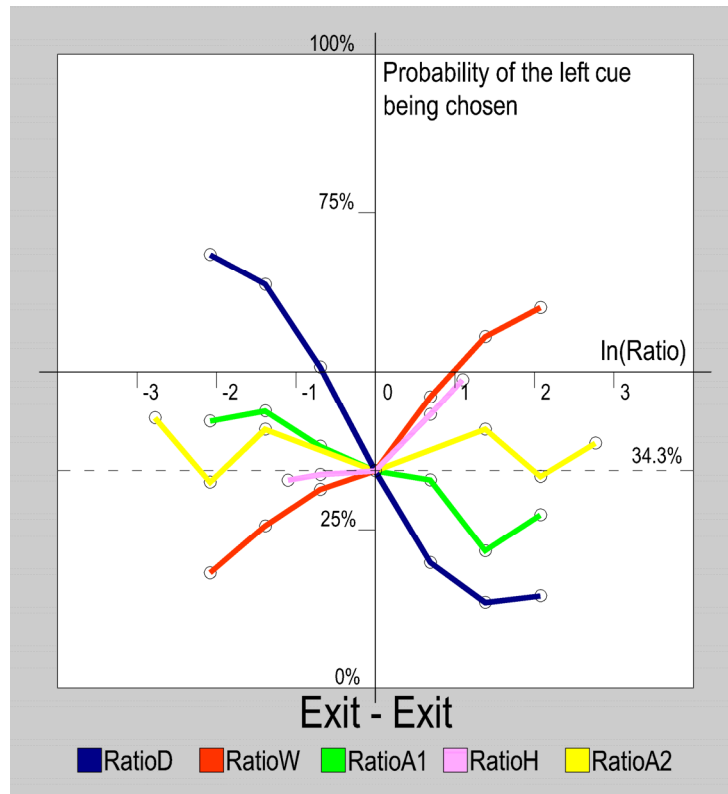


Figure 3.5-8 Relationship of the attributes and the probabilities in the E-E set

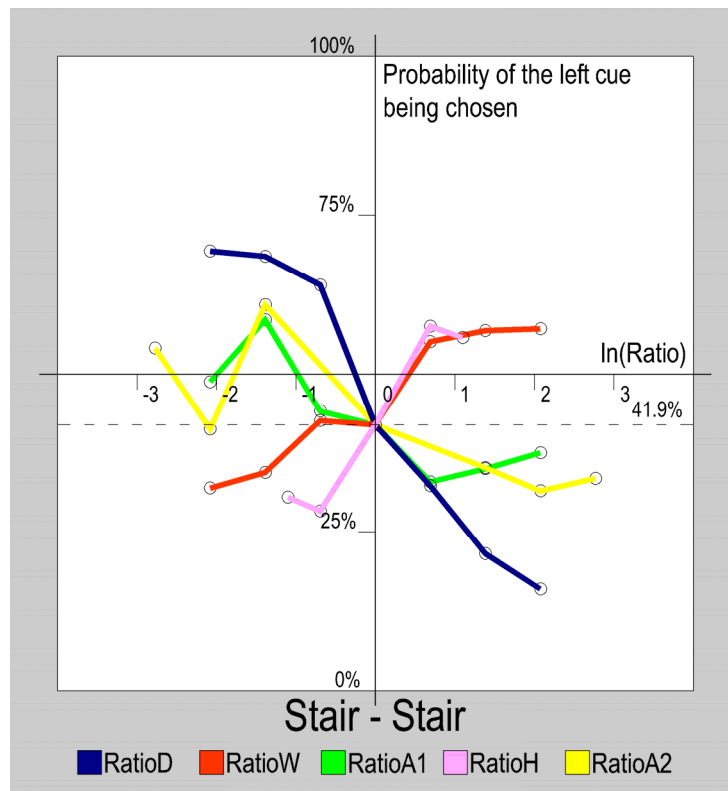


Figure 3.5-9 Relationship of the attributes and the probabilities in the S-S set

The First, it is noticed that in S-E set, the polylines standing for a left side Up Stair are above the polylines standing for a left side Exit (Fig.3.5-6). The former is almost above 50%, and the latter is almost below 50%, which means that the participants prefer Up Stair rather than Exit in most cases.

However, in the middle zone of the vertical axis, the polylines of the two groups weave into each other, which means that the participants can choose either side in spite of the type attribute, when the other attributes make the cue attractive enough. In summary, the attribute of cue type in the choices of S-E set has a significant impact on the function. In most cases, the participants prefer Up Stair rather than Exit. Only in some cases, the participants' preference goes to the opposite. This phenomenon matches the observed choices (Table 3.3-15), in which the Up Stair is chosen for much more times than Exit in the different cases.

Next, it is noticed that there is an obvious right side preference in the sets with the same cue types (Fig.3.5-7 ~ Fig.3.5-9). In the figures of set D-D, E-E, and S-S, the intersections of the polylines are all below 50% obviously (D-D: 36.8%, E-E: 34.3%, and S-S: 41.9%), which means that the participants choose the right cue when all the other attributes of the two cues in the pair are same. Similar right side preference can also be found in the behavioral literature (Güntürkün, 2003).

Table 3.5-13 Influence ability of the cue attributes

| Influence Ability | D-D | | E-E | | S-S | | S-E | |
|-------------------|---------------|------------------------|---------------|------------------------|---------------|------------------------|---------------|------------------------|
| | Cue Attribute | Max. Probability Range | Cue Attribute | Max. Probability Range | Cue Attribute | Max. Probability Range | Cue Attribute | Max. Probability Range |
| High ↑ | W | 33.4% | D | 54.8% | D | 53.3% | D | 40.7% Stair on left |
| | | | | | | | | 38.5% Exit on left |
| | D | 30.2% | W | 41.8% | A2 | 29.4% | W | 21.8% Stair on left |
| | | | | | | | | 30.1% Exit on left |
| | A1 | 25.5% | A1 | 22.1% | H | 29.3% | A1 | 14.9% Stair on left |
| | | | | | | | | 12.8% Exit on left |
| Low ↓ | A2 | 8.9% | H | 15.9% | A1 | 25.6% | H | 6.8% Stair on left |
| | | | | | | | | 6.6% Exit on left |
| | H | 7.8% | A2 | 10.2% | W | 25.2% | | |

Last, it is noticed that the five variables relating to the five attributes cover different probability ranges (Fig.3.5-6 ~ Fig.3.5-9), which reflect the different influence abilities of the attribute on the choice. The attributes are sorted according to their related probability ranges for the four cue pair types (Table 3.5-13). It is found that Distance is the most influential attribute in the cue pair type: E-E, S-S, S-E, which may support the nearest-exit assumption used prevalently in the existing evacuation simulation models as introduced in Chapter 2. However, Width is also indicated very important. It is the most influential attribute in the cue pair D-D and the second influential attribute in the cue pair E-E and S-E. According to the ranges, Width can be a very strong competitor to Distance to influence the participants' choices. Moreover, being second influential attribute in cue pair S-S, A2 is also a competitor to Distance, which means the angle that the participants must turn

to go upstairs is very influential in the choice between two Up Stairs. With these two competitors, it is believed that the nearest-exit assumption needs a revision. Besides Width and A2, it is noticed that A1 is influential just as the literatures suggest in Chapter 2. Height has a relatively low influence ability expect for S-S, in which the Height of Up Stair is reasonably a very important attribute to the evacuees in the underground space. In summary, the influence abilities of the five attributes are different depending on the cue pair type. It is very necessary to include all these attributes in the proposed model to predict the participants' choices.

In summary, according to the above analysis on the polylines indicating the relationship between the attributes and the probabilities, it is deduced that the participants have a stair-side preference with the attribute Type in the cue pair S-E, they have a right-side preference with the attribute Side in cue pair D-D, E-E, S-S, and they make choices according to all the rest five attributes to different extent.

3) Ratio-Probability Distributions of the Variables

To study the regression results at a micro level, the Ratio-Probability distributions of the five variables related to the five attributes are analyzed according to the surveyed nodes on the polylines (Fig.3.5-6 ~ Fig.3.5-9). Max r^2 is used as function to estimate a line according to the scattered nodes for every variable in every cue pair type (Appendix G). If the line indicates the probability and the variable increasing simultaneously, a mark “↑” is given to the left cue’s attribute related to the variable. Otherwise, a mark “↓” is given. The r^2 of the line estimation is also recorded (Table 3.5-14). First, the general trends of the distributions are analyzed according to the estimated lines. These trends indicate how the five attributes’ variation influences the predicted probability in general. Next, the various nonlinear features of the distributions are analyzed in detail.

Table 3.5-14 Overview of the Ratio-Probability curves

| | | Left cue’s attributes | | | | | | | | | |
|------------|---------------|-----------------------|-----------------|-------|-----------------|-------|-----------------|-------|-----------------|-------|-----------------|
| | | D | | W | | A1 | | H | | A2 | |
| | | Trend | r^2 of a line | Trend | r^2 of a line | Trend | r^2 of a line | Trend | r^2 of a line | Trend | r^2 of a line |
| D2D | | ↓ | 0.88 | ↑* | 0.96 | ↓* | 0.86 | ↑ | 0.38 | ↑ | 0.78 |
| E2E | | ↓* | 0.95 | ↑* | 0.98 | ↓ | 0.84 | ↑* | 0.86 | ↓ | 0.03 |
| S2S | | ↓* | 0.95 | ↑* | 0.92 | ↓ | 0.64 | ↑* | 0.91 | ↓ | 0.63 |
| S2E | E side | ↓* | 0.98 | ↑ | 0.85 | ↓ | 0.78 | ↑ | 0.52 | | |
| | S side | ↓* | 0.97 | ↑* | 0.92 | ↓ | 0.79 | ↑ | 0.51 | | |

Notes:

↓ The probability declines with the variable value increased

↑ The probability rises with the variable value increased

* The curve can be explained as a growth function ($r^2 \geq 0.95$)

First, it is noticed that the general trends of the Ratio-Probability distributions are reasonable. It is assumed that there is a general trend of the distribution indicated by the estimated line. This general trend can tell us how a left-cue attribute’s variation influences the probability of the left cue being chosen in general. For example, the trend indicated by the line of RatioD in cue pair S-S (Fig.3.5-10) tells us when the left-cue attribute’s value increases, the RatioD increases correspondingly and the probability of this left cue being chosen declines.

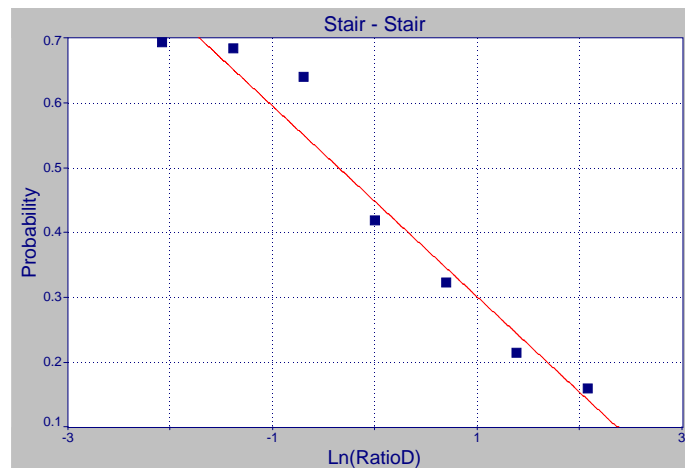


Figure 3.5-10 Ratio-Probability distribution of RatioD in S-S pair with line function

It is noticed that the general trends indicated by the lines of the four attributes D, W, A1, and H (Table 3.5-14) are reasonable according to the literature studies in Chapter 2. The lines of attribute D is always marked “↓”, which means that when RatioD increases, in other words the left cue being farther or the right cue being closer, the probability of the left cue being chosen declines. The lines of attribute W is always marked “↑”, which means that when RatioW increases, in other words the left cue being wider or the right cue being narrower, the probability of the left cue being chosen increases. The lines of attribute A1 is always marked “↓”, which means that when RatioA1 increases, in other words the left cue being farther from the view center or the right cue being closer to the view center, the probability of the left cue being chosen declines. The lines of attribute H is always marked “↑”, which means that when RatioH increases, in other words the left cue being higher or the right cue being lower, the probability of the left cue being chosen increases.

However, it seems there is a conflict in the general trends revealed by the three lines of the attribute A2 (Table 3.5-14). The two lines in cue pair E-E and S-S are marked “↓”, which means that when RatioA2 increases, in other words when the left cue needs the evacuee to turn more degree or the right cue needs the evacuee to turn less degree, the probability of the left cue being chosen declines. Such a general trend looks reasonable according to the minimized-turning-angle conclusion in the literature study of Chapter 2. In contrast, the line in cue pair D-D is marked “↑”, which seems unreasonable according to the above conclusion in Chapter 2. Actually, with the special feature of Doorway Entrance, such a mark is reasonable, too. As concluded in the observation experiment, a Doorway Entrance is attractive when the space behind it is not completely perceived. In other words, more space behind it being perceived leads to less attractiveness of the Doorway Entrance. When the attribute A2 of a Doorway Entrance become smaller, in other words when the evacuee can perceive more space behind it, the Doorway Entrance becomes less attractive. The probability of it being chosen declines, too. In contrast, a larger A2 value means that less space behind the Doorway Entrance can be perceived, which makes the Doorway Entrance more attractive. The probability of it being chosen increases correspondingly. Thus, it is reasonable that when the RatioA2 increases in D-D cue pair, in other words the left Doorway Entrance shows less space behind it or the right Doorway Entrance shows more space behind it, the probability of the left Doorway Entrance being chosen increases.

In brief, all the general trends of the Ratio-Probability distributions are reasonable. However, according to the descent average r^2 values in the estimated lines (D: 0.946, W: 0.926, A1: 0.782, H: 0.636, A2: 0.48), some attributes' Ratio-Probability distributions can't be explained as one linear function in detail.

Architectural Cue Model in Evacuation Simulation for Underground Space Design

Next, the nonlinear feature of these distributions is analyzed in detail. With the linear fitness of the attribute D and W relatively high, the analysis starts from the nonlinear feature of the remaining attributes' Ratio-Probability distributions.

It is believed that the nonlinear distribution of the A1 nodes is caused by the participant's behavior of turning head for cues on the side. There is not a facility to fix the participant's head direction in the experiment platform or in daily life, which means when the participant perceives a cue far away from the view center, he may unconsciously turn his head to the cue rapidly to check it within his focus. In fact, such small and rapid head turning is found in the recorded experiment videos. When the polylines of RatioA1 (Fig.3.5-7 ~ Fig.3.5-9) are studied, it is found that the two ends of the polyline always break the linear trend of its middle part. The logarithm values of the two ends are 2.08 and -2.08, at which the ratios are 8:1 and 1:8. According to the encoding plans (Table 3.5-3 ~ Table 3.5-5), it is found that at these ratios, one cue is 60 degree away from the view direction and the other is 7.5 degree away from the view direction. According to the literature study in the end of Chapter 2, the human being's binocular view field is about 120 degree, each side 60 degree. With the reduced perception range by the emotional arousal under stress (Ozel, 1993) and the different visual acuity between fovea and the rest retina (Lam, 1992), the cue 60 degree away from the view center will induce the participant to turn his head to have a clear look at it. With his head turning, the actual A1 value reduces to much less than 60 degree according to the A1 definition. For example, in the cue pair with RatioA1 as 8:1, the A1 of the left cue is 60 degree and the A1 of the right is 7.5 degree. If the participant turns his head more than 30 degree to the left, the actual A1 of the left cue reduces to less than 30 degree. Then the actual RatioA1 is less than 4:1, which means the probability of RatioA1 8:1 will actually be higher than probability of RatioA1 4:1. Vice versa the Ratio 1:8 will actually be lower than the probability of RatioA1 1:4, if the participant turns his head more than 30 degree to the right. As a proof, the polylines of RatioA1 in D-D, E-E, and S-S match the above analysis. The left part of the polyline of RatioA1 in S-E matches it, too. In short, the nonlinear feature of the attribute A1's distributions reflects the human beings' head turning behavior in both the experiment and the daily life.

After the review on the experiment process and the literatures, no clue is found to analyze the nonlinear feature of the attribute H and A2's distributions. However, during this investigation, it is found that eleven of twenty three (48%) distributions match a specific nonlinear function with the r^2 value higher than 0.95 (Table 3.5-14, details in Appendix G). For example, the Ratio-Probability distribution of RatioD in cue pair S-S can matches this function very well with the r^2 value as 0.99 (Fig.3.5-11). This function is proposed in 1838 by the mathematician Verhulst to describe demographic growth processes, which is also used frequently to describe the process of some thing satisfying the human need (Arentze & Timmermans, 2006). The curve of the function has an "S" shape on the XY plane. Y stands for the need satisfied. It has an upper boundary and a lower boundary, which means that the need can never be fully satisfied. X stands for something to meet the need. When X increases or decreases an amount initially from the curve center, part of the need gets satisfied. However, only a smaller part of the need can be satisfied when X changes the same amount but with the X position farther away from the curve center. It is just like the marginal effect. In fact, the choosing behavior with two cues is a sort of need satisfaction. To feel taking the right way is the need in the route searching process. The confidence supported by the difference between the two cues' attributes (the variable) is something to satisfy the need. Thus, it is believed that such a growth function fit the Ratio-Probability distributions of the variables not only in shape but also in the concept.

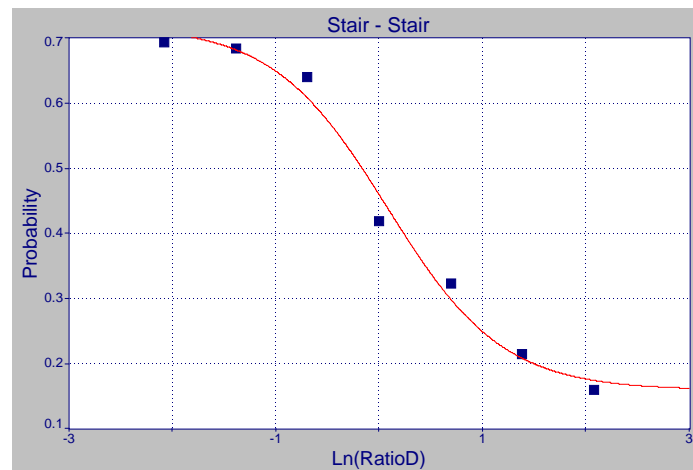


Figure 3.5-11 Ratio-Probability distribution of RatioD in S-S pair with growth function

In brief, as indicated by the different r^2 values of the line function and the above analysis, the five variables relating to the five attributes have different nonlinear features in their Ratio-Probability distributions. Some of them are explainable. Some are not.

3.5.5 Conclusions

In this estimation experiment supported by the CAVE-based Conjoint Analysis approach, the qualitative conclusions on the four information sources offering local architectural cues are transited into the quantitative variables driving the computational model through the preference prediction function. With this function the computational model can quantitatively estimate the probability of the evacuees' choice for the four cue pair types (D-D, E-E, S-S, and S-E).

As the most important result of this experiment, a set of estimated parameters, B values, corresponding to all the variable levels and ratio values is extracted from the regression report as a datasheet (Table 3.5-15). Generally, there are four columns of B values for the four cue pair types. The B value is indicated on the right of the ratio, which is defined as the ratio of the left cue's attribute value to the right cue's attribute value. Notably, in the column of S-E, there are two sub-groups of B values for RatioW. If the cue on the left is an Up Stair, the B value in the sub-group "Stair on Left" should be used. If it is an Exit, the B value in the sub-group "Exit on Left" should be used.

Before the function is applied in the proposed model, it is analyzed at different levels. At a macro level, it is found that the estimated function does have the prediction ability to a certain extent and such an ability changes reasonably with the different cue pair type. At a meso level, it is found that all the seven attributes of the local architectural cues are all influential in the choice. The stair-side preference in S-E pair, the right-side preference in D-D, E-E, S-S pairs, and the different influence abilities of the attributes related to the five variables are revealed. At a micro level, it is found that the general trends of the Ratio-Probability distributions of the five variables are reasonable. In a more detailed analysis, the various nonlinear features of these distributions are revealed.

With the nonlinear features revealed in the analysis, it has to be decided how to find a B value for an unsurveyed attribute's ratio, before the function is applied to the model. It is found that on the one hand, with the general trends indicating different r^2 values for a linear function, it is not proper to use one line function to cover all the unsurveyed ratios. On the other hand, with the various

Architectural Cue Model in Evacuation Simulation for Underground Space Design

nonlinear features in the distributions, the experiment doesn't have enough surveyed ratios to deduce a proper nonlinear function covering all the unsurveyed ratios. Thus, the polyline connecting the surveyed ratios is used to cover the whole ratio value range, which means that the linear interpolation method can be used to calculate the unknown B value for an unsurveyed ratio according to the B values of the two neighboring surveyed ratios. With this strategy, the limited surveyed B values can enable the function to work on any ratio value inside the defined ranges.

Finally, with the above problem solved, the preference prediction function can be applied in the proposed model, in which it will be used to sort the local architectural cues in the cue pool for a simulated evacuee. According to the above analyses, it is believed that this function is reasonable, and to a certain extent it is able to predict the probability of the choice on the cue pair with any attribute ratio inside the defined ranges. Notably, the predicted chosen cue reflects the shared preference of the most participants in the estimation experiment, which means that the prediction error greatly correlates to the disparity between the predicted people and the participants in the estimation experiment. With the function built, a computer-based prototype will be built to simulate the evacuee's route searching process in the following.

Table 3.5-15 Estimated B values

| | | D-D | | E-E | | S-S | | S-E | | |
|---------------------|---------|---------------|---------|---------------|---------|---------------|---------|---------------|------------|--------|
| | | Ratio (L : R) | B Value | Ratio (L : R) | B Value | Ratio (L : R) | B Value | Ratio (L : R) | B Value | |
| Levels | RatioA1 | 1 | 1 : 8 | .770 | 1 : 8 | .661 | 1 : 8 | .459 | 1 : 8 | .484 |
| | | 2 | 1 : 4 | .935 | 1 : 4 | .726 | 1 : 4 | .854 | 1 : 4 | .603 |
| | | 3 | 1 : 2 | .668 | 1 : 2 | .495 | 1 : 2 | .272 | 1 : 2 | .624 |
| | | 4 | 1 : 1 | .357 | 1 : 1 | .327 | 1 : 1 | .184 | 1 : 1 | .412 |
| | | 5 | 2 : 1 | .044 | 2 : 1 | .262 | 2 : 1 | -.202 | 2 : 1 | .312 |
| | | 6 | 4 : 1 | -.177 | 4 : 1 | -.307 | 4 : 1 | -.110 | 4 : 1 | .186 |
| | | 7 | 8 : 1 | 0 | 8 : 1 | 0 | 8 : 1 | 0 | 8 : 1 | 0 |
| | RatioD | 1 | 1 : 8 | 1.217 | 1 : 8 | 2.539 | 1 : 8 | 2.473 | 1 : 8 | 1.840 |
| | | 2 | 1 : 4 | 1.033 | 1 : 4 | 2.331 | 1 : 4 | 2.433 | 1 : 4 | 1.650 |
| | | 3 | 1 : 2 | 1.150 | 1 : 2 | 1.798 | 1 : 2 | 2.232 | 1 : 2 | 1.448 |
| | | 4 | 1 : 1 | .382 | 1 : 1 | 1.120 | 1 : 1 | 1.329 | 1 : 1 | .876 |
| | | 5 | 2 : 1 | .304 | 2 : 1 | .373 | 2 : 1 | .915 | 2 : 1 | .654 |
| | | 6 | 4 : 1 | -.068 | 4 : 1 | -.087 | 4 : 1 | .365 | 4 : 1 | .182 |
| | | 7 | 8 : 1 | 0 | 8 : 1 | 0 | 8 : 1 | 0 | 8 : 1 | 0 |
| RatioH | 1 | 1 : 3 | -.192 | 1 : 3 | -.663 | 1 : 3 | -1.053 | 1 : 3 | -.199 | |
| | 2 | 1 : 2 | -.333 | 1 : 2 | -.623 | 1 : 2 | -1.160 | 1 : 2 | -.296 | |
| | 3 | 1 : 1 | -.226 | 1 : 1 | -.597 | 1 : 1 | -.555 | 1 : 1 | -.271 | |
| | 4 | 2 : 1 | -.239 | 2 : 1 | -.219 | 2 : 1 | .074 | 2 : 1 | -.167 | |
| | 5 | 3 : 1 | 0 | 3 : 1 | 0 | 3 : 1 | 0 | 3 : 1 | 0 | |
| RatioA2 | 1 | 1 : 16 | -.280 | 1 : 16 | .166 | 1 : 16 | .850 | | | |
| | 2 | 1 : 8 | -.383 | 1 : 8 | -.269 | 1 : 8 | .334 | | | |
| | 3 | 1 : 4 | -.194 | 1 : 4 | .092 | 1 : 4 | 1.132 | | | |
| | 4 | 1 : 1 | -.214 | 1 : 1 | -.188 | 1 : 1 | .362 | | | |
| | 5 | 4 : 1 | -.180 | 4 : 1 | .092 | 4 : 1 | .075 | | | |
| | 6 | 8 : 1 | -.030 | 8 : 1 | -.228 | 8 : 1 | -.090 | | | |
| | 7 | 16 : 1 | 0 | 16 : 1 | 0 | 16 : 1 | 0 | | | |
| RatioW | 1 | 1 : 8 | -1.449 | 1 : 8 | -1.909 | 1 : 8 | -1.043 | Stair on Left | 0.1125 : 1 | .268 |
| | 2 | 1 : 4 | -1.125 | 1 : 4 | -1.471 | 1 : 4 | -.932 | | 0.225 : 1 | .258 |
| | 3 | 1 : 2 | -.897 | 1 : 2 | -1.188 | 1 : 2 | -.585 | | 0.45 : 1 | .439 |
| | 4 | 1 : 1 | -.842 | 1 : 1 | -1.055 | 1 : 1 | -.612 | | 0.9 : 1 | .792 |
| | 5 | 2 : 1 | -.296 | 2 : 1 | -.567 | 2 : 1 | -.083 | | 1.8 : 1 | .821 |
| | 6 | 4 : 1 | -.081 | 4 : 1 | -.186 | 4 : 1 | -.012 | | 3.6 : 1 | 1.178 |
| | 7 | 8 : 1 | 0 | 8 : 1 | 0 | 8 : 1 | 0 | | 7.2 : 1 | 1.088 |
| | 8 | | | | | | | Exit on Left | 1 : 7.2 | -1.086 |
| | 9 | | | | | | | | 1 : 3.6 | -.606 |
| | 10 | | | | | | | | 1 : 1.8 | -.544 |
| | 11 | | | | | | | | 1 : 0.9 | -.459 |
| | 12 | | | | | | | | 1 : 0.45 | -.109 |
| | 13 | | | | | | | | 1 : 0.225 | .311 |
| | 14 | | | | | | | | 1 : 0.1125 | 0 |
| Interception | | .003 | | -.255 | | -1.033 | | -1.334 | | |

Notes: L: left cue; R: right cue

3.6 Prototype of the Model

With the four further questions in the end of Chapter 2 answered in the above sections, all the components in the computational model framework are understood. According to it, a computer-based prototype called SpaceSensor is built to achieve the two aims raised in the beginning of this chapter. On the one hand, SpaceSensor visually explains how the evacuee searches his route to the safety in the complex public underground space design within the defined application context and evacuation scenario. On the other hand, SpaceSensor supports the architect-oriented criterion LEEI for the evaluation on the designs. In the following, an overview of SpaceSensor is first introduced. Next, two demonstrations are discussed to illustrate how these two aims are achieved with it.

3.6.1 Overview

SpaceSensor (Fig.3.6-1) is developed in Visual Basic v6.0 and includes three steps in its operation. First, the geometric information of the space design in AutoCAD is exported into an independent data file. Next, with such a file, SpaceSensor can simulate the process that an evacuee searches the route to the safety from a starting point according to the visually perceived local architectural cues and calculate the criterion LEEI for this starting point. Last, the simulated route is imported into AutoCAD in overlay upon the original design to enable the architect’s further analysis. Additionally, a set of files containing all the information of the evacuation process is generated for detail analysis. The detailed operations and the generated files are introduced in Appendix E.

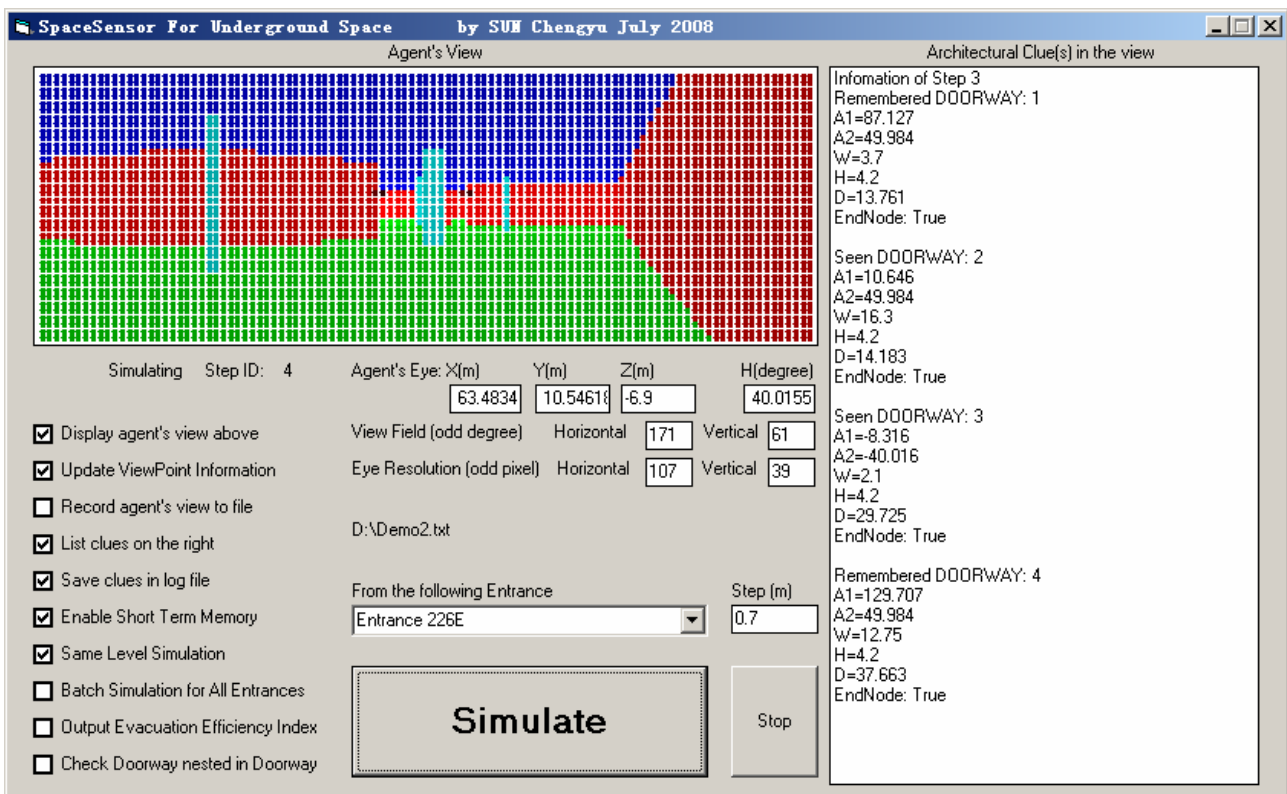


Figure 3.6-1 User interface of SpaceSensor

Two things worth mention here are the strategy to select the cue from the cue pool and the strategy to calculate the angular attribute ratios in SpaceSensor.

A deterministic strategy is used to select the cue from the cue pool in SpaceSensor. According to the model framework (Fig.3.4-1), the simulated evacuee will choose the cue with the highest probability in a sorted cue pool. In fact, there are two options to find such a cue. One option is to use a deterministic strategy, in which the simulated evacuee just takes the top cue in the sorted cue pool. No matter how many times the prototype runs, it results in the same evacuation route. The other option is to use a stochastic strategy, in which every cue can have a probability to be taken correlating to its rank in the sorted cue pool. The top cue has the biggest probability, and the bottom cue has the smallest one. If the prototype runs for many times, it will result in a set of different evacuation traces, which can reflect these probabilities. For the architect-oriented usage demanding the rapid simulation and the good readability, the prototype is built with the deterministic strategy. Consequently, the simulated route in SpaceSensor only reflects the preference shared by the most participants in the estimation experiment.

A specific bin-based strategy is used to calculate the angular attribute ratios in SpaceSensor. According to the preference prediction function (Eq.2), RatioA1 and RatioA2 are the ratios of two angular values. Unlike the other kinds of attribute values, an angular value can be zero, which is a big problem for the ratio calculation. According to bin-based strategy used by other egoistic pedestrian models (Turner & Penn, 2002; Antonini & Bierlaire, 2005), the angular value range is divided into several bins. A value within the boundaries of a bin will be treated as the representative value of the bin. There is one definition for bins of A1 (Table 3.6-1) and two definitions for bins of A2 (Table 3.6-2 and Table 3.6-3)

Table 3.6-1 Bin definition of A1 for all the three cue types

| Representative Value (degree) | Bin Boundaries (degree) |
|--------------------------------------|--------------------------------|
| 7.5 | [0, 11.25) |
| 15 | [11.25, 22.5) |
| 30 | [22.5, 45) |
| 60 | [45, 180) |

Table 3.6-2 Bin definition of A2 for Doorway Entrance and Exit

| Representative Value (degree) | Bin Boundaries (degree) |
|--------------------------------------|--------------------------------|
| 5 | [0, 12.5) |
| 20 | [12.5, 30) |
| 40 | [30, 60) |
| 80 | [60, 180) |

Table 3.6-3 Bin definition of A2 for Up Stair

| Representative Value (degree) | Bin Boundaries (degree) |
|--------------------------------------|--------------------------------|
| 10 | [0,25) |
| 40 | [25,60) |
| 80 | [60,120) |
| 160 | [120,180] |

3.6.2 Demonstration on Route Searching Process

In the first demonstration, it is revealed how the sequential decisions are made in the computational model according to the log file of SpaceSensor, which reflects all of the previous conclusions synthetically on how the evacuee searches the route to the safety in the complex public underground space designs.

A three-story underground space design is used in the demonstration. It is designed for one of the subway stations to be constructed in China. The B3 level is the platform of the subway. The B2 (Fig.3.6-2) and B1 (Fig.3.6-3) levels are commercial spaces, which connect with the commercial buildings around the subway station.

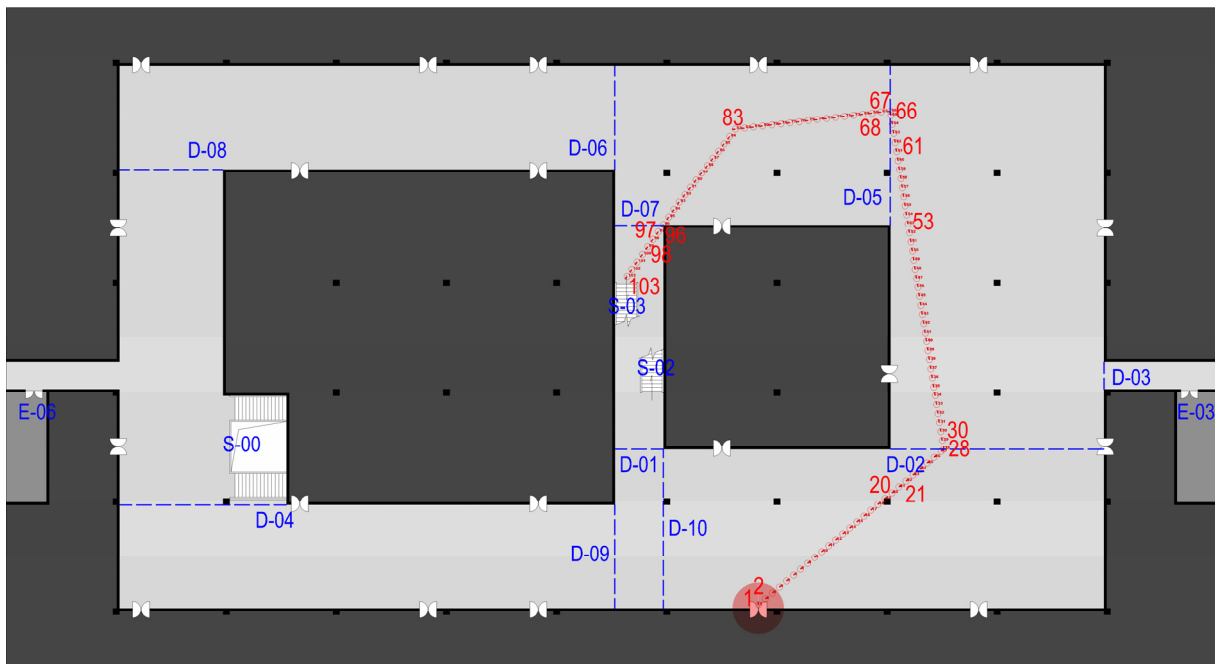


Figure 3.6-2 Plan of B2 level with one route

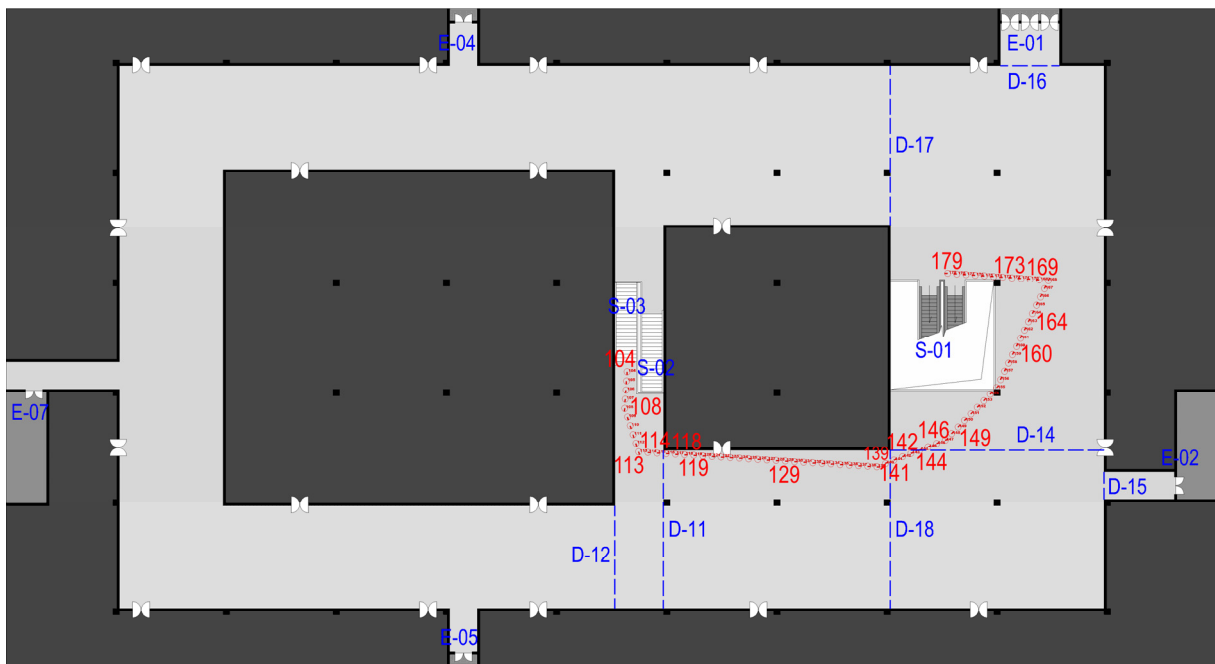


Figure 3.6-3 Plan of B1 level with one route

The space design of the Exit Access region in light grey is evaluated. It is assumed that the visitors enter this space from the platform through Stair S-00 on B2 level and go shopping in the Occupied Rooms region in dark grey. SpaceSensor simulates the process that an evacuee searches the route to the safety from the starting point in pink circle to the Exit region in moderate grey.

With the default settings, the simulated evacuee arrives at the ground floor through S-01 in 180 steps. In the following, the simulated evacuee’s whole decision making process with the cues (Table 3.6-4) in the detailed explanations is revealed according to the log file generated by SpaceSensor. Notably, with the focus on the important steps involving the changes in the cue pool or the change of the selected cue, the steps between any two such important steps are skipped in the following explanations.

Table 3.6-4 Decision process with the cues in every step

| Step ID | Check & Process Arrival Cues | | | | | See | | | Choose |
|---------|-------------------------------|----------------------|-------------------------------------|----------------------------------------------------|----------------------------------------------|------------------------------|-----------------------------------------|----------------------------------------------------------|------------------|
| | The Cue Reached as the Safety | The Up Stair Reached | The Doorway Entrance Passed Through | The Reached Doorway Entrance Selected in Last Step | Cues in Cue Pool | The Cues Seen in This Step | The Cues Marked Remembered in This Step | Cues in Cue Pool | The Cue Selected |
| 1 | | | | | | D-01 D-02 D-03 D-04 | | D-01 (s) D-02 (s) D-03 (s) D-04 (s) | D-02 |
| 2 | | | | | D-01 (s) D-02 (s) D-03 (s) D-04 (s) | D-02 D-03 | D-01 D-04 | D-01 (r) D-02 (s) D-03 (s) D-04 (r) | D-02 |
| 20 | | | | | D-01 (r) D-02 (s) D-03 (s) D-04 (r) | D-03 | D-02 | D-01 (r) D-02 (r) D-03 (s) D-04 (r) | D-02 |
| 21 | | | | | D-01 (r) D-02 (r) D-03 (s) D-04 (r) | D-03 D-05 | | D-01 (r) D-02 (r) D-03 (s) D-04 (r) D-05 (s) | D-02 |
| 28 | | | D-02 | D-02 | D-03 (s) D-05 (s) | | | | |
| 30 | | | | | D-03 (s) D-05 (s) | D-05 | D-03 | D-03 (r) D-05 (s) | D-05 |
| 53 | | | | | D-03 (r) D-05 (s) | D-06 | D-05 | D-03 (r) D-05 (r) D-06 (s) | D-05 |
| 61 | | | | | D-03 (r) D-05 (r) D-06 (s) | | D-06 | D-03 (r) D-05 (r) D-06 (r) | D-05 |
| 66 | | | D-05 | | D-03 (r) D-05 (r) D-06 (r) | D-07 D-08 | | D-03 (r) D-06 (r) D-07 (s) D-08 (s) | D-08 |
| 67 | | | | | D-03 (r) D-06 (r) D-07 (s) D-08 (s) | D-07 D-08 | | D-03 (r) D-06 (r) D-07 (s) D-08 (s) | D-06 |

Architectural Cue Model in Evacuation Simulation for Underground Space Design

| Step ID | Check & Process Arrival Cues | | | | | See | | | Choose |
|---------|-------------------------------|----------------------|-------------------------------------|----------------------------------------------------|----------------------------------------------------------------------|------------------------------|-----------------------------------------|----------------------------------------------------------------------------------|------------------|
| | The Cue Reached as the Safety | The Up Stair Reached | The Doorway Entrance Passed Through | The Reached Doorway Entrance Selected in Last Step | Cues in Cue Pool | The Cues Seen in This Step | The Cues Marked Remembered in This Step | Cues in Cue Pool | The Cue Selected |
| 68 | | | | | D-03 (r) D-06 (r) D-07 (s) D-08 (s) | D-07 | D-08 | D-03 (r) D-06 (r) D-07 (s) D-08 (r) | D-06 |
| 83 | | | | | D-03 (r) D-06 (r) D-07 (s) D-08 (r) | D-07 S-03 | | D-03 (r) D-06 (r) D-07 (s) D-08 (r) S-03 (s) | S-03 |
| 96 | | | | | D-03 (r) D-06 (r) D-07 (s) D-08 (r) S-03 (s) | D-07 D-09 S-02 S-03 | | D-03 (r) D-06 (r) D-07 (s) D-08 (r) D-09 (s) S-02 (s) S-03 (s) | S-03 |
| 97 | | | D-07 | | D-03 (r) D-06 (r) D-08 (r) D-09 (s) S-02 (s) S-03 (s) | D-09 S-02 S-03 | | D-03 (r) D-06 (r) D-08 (r) D-09 (s) S-02 (s) S-03 (s) | S-03 |
| 98 | | | | | D-03 (r) D-06 (r) D-08 (r) D-09 (s) S-02 (s) S-03 (s) | D-09 D-10 S-02 S-03 | | D-03 (r) D-06 (r) D-08 (r) D-09 (s) D-10 (s) S-02 (s) S-03 (s) | S-03 |
| 103 | | S-03 | | | | | | | |
| 104 | | | | | | D-11 D-12 | | D-11 (s) D-12 (s) | D-12 |
| 108 | | | | | D-11 (s) D-12 (s) | D-11 D-12 | | D-11 (s) D-12 (s) | D-11 |
| 113 | | | | | D-11 (s) D-12 (s) | D-12 E-02 | D-11 | D-11 (r) D-12 (s) E-02 (s) | E-02 |
| 114 | | | | | D-11 (r) D-12 (s) E-02 (s) | E-02 | D-12 | D-11 (r) D-12 (r) E-02 (s) | E-02 |
| 118 | | | | | D-11 (r) D-12 (r) E-02 (s) | D-14 E-02 | | D-11 (r) D-12 (r) D-14 (s) E-02 (s) | E-02 |
| 119 | | | | | D-11 (r) D-12 (r) D-14 (s) E-02 (s) | D-14 D-15 E-02 | | D-11 (r) D-12 (r) D-14 (s) D-15 (s) E-02 (s) | E-02 |

| Step ID | Check & Process Arrival Cues | | | | See | | | Choose | |
|---------|-------------------------------|----------------------|-------------------------------------|----------------------------------------------------|----------------------------------------------------------------------------------------------|--------------------------------------|-----------------------------------------|----------------------------------------------------------------------------------------------|------------------|
| | The Cue Reached as the Safety | The Up Stair Reached | The Doorway Entrance Passed Through | The Reached Doorway Entrance Selected in Last Step | Cues in Cue Pool | The Cues Seen in This Step | The Cues Marked Remembered in This Step | Cues in Cue Pool | The Cue Selected |
| 129 | | | | | D-11 (r) D-12 (r) D-14 (s) D-15 (s) E-02 (s) | D-14 E-02 | D-15 | D-11 (r) D-12 (r) D-14 (s) D-15 (r) E-02 (s) | E-02 |
| 139 | | | | | D-11 (r) D-12 (r) D-14 (s) D-15 (r) E-02 (s) | D-14 E-02 S-01 | | D-11 (r) D-12 (r) D-14 (s) D-15 (r) E-02 (s) S-01 (s) | S-01 |
| 141 | | | | | D-11 (r) D-12 (r) D-14 (s) D-15 (r) E-02 (s) S-01 (s) | D-16 E-02 S-01 | D-14 | D-11 (r) D-12 (r) D-14 (r) D-15 (r) D-16 (s) E-02 (s) S-01 (s) | S-01 |
| 142 | | | | | D-11 (r) D-12 (r) D-14 (r) D-15 (r) D-16 (s) E-02 (s) S-01 (s) | D-16 D-17 E-02 S-01 | | D-11 (r) D-12 (r) D-14 (r) D-15 (r) D-16 (s) D-17 (s) E-02 (s) S-01 (s) | S-01 |
| 144 | | | D-14 | | D-11 (r) D-12 (r) D-15 (r) D-16 (s) D-17 (s) E-02 (s) S-01 (s) | D-16 D-17 E-02 S-01 | | D-11 (r) D-12 (r) D-15 (r) D-16 (s) D-17 (s) E-02 (s) S-01 (s) | S-01 |
| 146 | | | | | D-11 (r) D-12 (r) D-15 (r) D-16 (s) D-17 (s) E-02 (s) S-01 (s) | D-16 D-17 E-01 E-02 S-01 | | D-11 (r) D-12 (r) D-15 (r) D-16 (s) D-17 (s) E-01 (s) E-02 (s) S-01 (s) | S-01 |
| 149 | | | | | D-11 (r) D-12 (r) D-15 (r) D-16 (s) D-17 (s) E-01 (s) E-02 (s) S-01 (s) | D-16 D-17 E-01 S-01 | E-02 | D-11 (r) D-12 (r) D-15 (r) D-16 (s) D-17 (s) E-01 (s) E-02 (r) S-01 (s) | S-01 |

Architectural Cue Model in Evacuation Simulation for Underground Space Design

| Step ID | Check & Process Arrival Cues | | | | See | | | Choose | |
|---------|-------------------------------|----------------------|-------------------------------------|----------------------------------------------------|----------------------------------------------------------------------------------------------------------|----------------------------|-----------------------------------------|----------------------------------------------------------------------------------------------------------|------------------|
| | The Cue Reached as the Safety | The Up Stair Reached | The Doorway Entrance Passed Through | The Reached Doorway Entrance Selected in Last Step | Cues in Cue Pool | The Cues Seen in This Step | The Cues Marked Remembered in This Step | Cues in Cue Pool | The Cue Selected |
| 160 | | | | | D-11 (r) D-12 (r) D-15 (r) D-16 (s) D-17 (s) E-01 (s) E-02 (r) S-01 (s) | D-17 E-01 S-01 | D-16 | D-11 (r) D-12 (r) D-15 (r) D-16 (r) D-17 (s) E-01 (s) E-02 (r) S-01 (s) | S-01 |
| 164 | | | | | D-11 (r) D-12 (r) D-15 (r) D-16 (r) D-17 (s) E-01 (s) E-02 (r) S-01 (s) | E-01 S-01 | D-17 | D-11 (r) D-12 (r) D-15 (r) D-16 (r) D-17 (r) E-01 (s) E-02 (r) S-01 (s) | S-01 |
| 169 | | | | | D-11 (r) D-12 (r) D-15 (r) D-16 (r) D-17 (r) E-01 (s) E-02 (r) S-01 (s) | D-18 E-01 S-01 | | D-11 (r) D-12 (r) D-15 (r) D-16 (r) D-17 (r) D-18 (s) E-01 (s) E-02 (r) S-01 (s) | S-01 |
| 173 | | | | | D-11 (r) D-12 (r) D-15 (r) D-16 (r) D-17 (r) D-18 (s) E-01 (s) E-02 (r) S-01 (s) | D-18 S-01 | E-01 | D-11 (r) D-12 (r) D-15 (r) D-16 (r) D-17 (r) D-18 (s) E-01 (r) E-02 (r) S-01 (s) | S-01 |
| 179 | | S-01 | | | | | | | |
| 180 | S-01 | | | | | | | | |

Notes: (s): Seen; (r): Remembered.

Step 1 (Pink Circle): The simulated evacuee perceives 4 local architectural cues: D-01, D-02, D-03, and D-04 (Fig.3.6-2) with their attributes (Table 3.6-5). Such information is stored into the cue pool in his memory. According to these attributes, the simulated evacuee compares the probabilities of every two cues to be chosen (Table 3.6-6) in the cue pool. He finds that only the cue D-02 always has more probability than the others. Thus, he selects the cue D-02 as the goal of next step to approach.

Table 3.6-5 Attributes of the cues in the cue pool

| Cue | Attribute Value | | | | |
|------|-----------------|--------------|--------------|----------------|--------------|
| | A1 (degree) | D (meter) | H (meter) | A2 (degree) | W (meter) |
| D-01 | 31.37 | 13.900 | 4.200 | 0 | 3.700 |
| D-02 | -40.29 | 15.560 | 4.200 | 0 | 16.300 |
| D-03 | -57.93 | 31.110 | 4.200 | -90 | 2.100 |
| D-04 | 78.05 | 36.785 | 4.200 | 0 | 12.750 |

Table 3.6-6 Paired comparisons

| | | Right Cue | | | |
|----------|------|-----------|-------|-------|------|
| | | D-01 | D-02 | D-03 | D-04 |
| Left Cue | D-01 | | 32.2% | 71.1% | |
| | D-02 | | | 78.9% | |
| | D-03 | | | | |
| | D-04 | 40.9% | 26.1% | 54.6% | |

Notes: The percentage is the probability of the left cue being chosen.

Step 2: The simulated evacuee can't see the cues D-01 and D-04, which are visible in the last step. Thus, these two cues are marked "Remembered".

Step 20: The simulated evacuee can't see the cues D-02, which are visible in the last step. Thus, this cue is marked "Remembered".

Step 21: The simulated evacuee perceives a new cue D-05. However, after paired comparisons, he still selects the cue D-02.

Step 28: The simulated evacuee arrives at the entrance of the cue D-02. Thus, D-02 itself is removed from the cue pool as a passed through Doorway Entrance. Furthermore, as a selected Doorway Entrance in the last step, all the cues marked "Remembered" (D-01 and D-04) in the cue pool are also removed. Among the rest cues, he selects the cue D-05 to approach.

Step 30: The simulated evacuee can't see the cues D-03, which are visible in the last step. Thus, this cue is marked "Remembered".

Step 53: The simulated evacuee perceives a new cue D-06 and can't see the cue D-05, which is visible in the last step. Thus, the cue D-05 are marked "Remembered". However, after paired comparisons, he still selects the cue D-05.

Step 61: The simulated evacuee can't see the cues D-06, which is visible in the last step. Thus, the cue D-06 is marked "Remembered".

Step 66: The simulated evacuee perceives two new cues D-07 and D-08. Among the cues in cue pool, he selects the cue D-08 to approach. Meanwhile, he passes through the cue D-05. Thus, D-05 itself is removed from the cue pool.

Step 67: With the new position, the simulated evacuee selects the cue D-06.

Step 68: The simulated evacuee can't see the cues D-08, which are visible in the last step. Thus, this cue is marked "Remembered".

Step 83: The simulated evacuee perceives a new cue S-03. According to the preference concluded in the observation experiment, SpaceSensor assumes that the simulated evacuee will always select Up Stair in an Up Stair-Doorway Entrance pair. Thus, the cue S-03 is selected against all the other Doorway Entrances in the cue pool.

Step 96: The simulated evacuee perceives two new cues S-02 and D-09. However, after paired comparisons, he still selects the cue S-03.

Step 97: The simulated evacuee passes through the cue D-07. Thus, it is removed from the cue

pool.

Step 98: The simulated evacuee perceives a new cue D-10. However, after paired comparisons, he still selects the cue S-03.

Step 103: The simulated evacuee is 0.5 meter to the Up Stair S-03, which is shorter than the step distance 0.7 meter. SpaceSensor assumes the simulated evacuee arrives at the Up Stair S-03 and moves him upstairs. Meanwhile, the cue pool is emptied for the new B1 level.

Step 104: The simulated evacuee perceives two cues D-11 and D-12. According to the paired comparison, he selects the cue D-12.

Step 108: With the new position, the simulated evacuee selects the cue D-11.

Step 113: The simulated evacuee perceives a new cue E-02. According to the preference concluded in the observation experiment, SpaceSensor assumes that the simulated evacuee will always select Exit in an Exit-Doorway Entrance pair. Thus, the cue E-02 is selected against all the other Doorway Entrances in the cue pool. Meanwhile, the cue D-11 is not in the vision, which is visible in the last step. Thus, cue D-11 is marked "Remembered".

Step 114: The cue D-12 is not in the vision, which is visible in the last step. Thus, cue D-12 is marked "Remembered".

Step 118: The simulated evacuee perceives a new cue D-14. However, after paired comparisons, he still selects the cue E-02.

Step 119: The simulated evacuee perceives a new cue D-15. However, after paired comparisons, he still selects the cue E-02.

Step 129: The cue D-15 is not in the vision, which is visible in the last step. Thus, cue D-15 is marked "Remembered".

Step 139: The simulated evacuee perceives a new cue S-01. After paired comparisons, he selects the cue S-01 as the goal of next step.

Step 141: The simulated evacuee perceives a new cue D-16. However, after paired comparisons, he still selects the cue S-01. Meanwhile, the cue D-14 is not in the vision, which is visible in the last step. Thus, cue D-14 is marked "Remembered".

Step 142: The simulated evacuee perceives a new cue D-17. However, after paired comparisons, he still selects the cue S-01.

Step 144: The simulated evacuee passes through the cue D-14. Thus, D-14 itself is removed from the cue pool.

Step 146: The simulated evacuee perceives a new cue E-01. However, after paired comparisons, he still selects the cue S-01.

Step 149: The cue E-02 is not in the vision, which is visible in the last step. Thus, cue E-02 is marked "Remembered".

Step 160: The cue D-16 is not in the vision, which is visible in the last step. Thus, cue D-16 is marked "Remembered".

Step 164: The cue D-17 is not in the vision, which is visible in the last step. Thus, cue D-17 is marked "Remembered".

Step 169: The simulated evacuee perceives a new cue D-18. However, after paired comparisons, he still selects the cue S-01.

Step 173: The cue E-01 is not in the vision, which is visible in the last step. Thus, cue E-01 is marked "Remembered".

Step 179: The simulated evacuee is 0.63 meter to the Up Stair S-01, which is shorter than the step distance 0.7 meter. SpaceSensor assumes the simulated evacuee arrives at the Up Stair S-01 and moves him upstairs to the ground floor. Meanwhile, the cue pool is emptied.

Step 180: The simulation ends, when the simulated evacuee finds himself already at the ground floor (the safety).

After the simulation, SpaceSensor reports that the shortest route to the safety from the starting point is to approach E-03, which is 36.97 meter. The simulated route terminated at Stair S-01 is 126 meters excluding the movement on the stairs. According to the definition of LEEI (Eq. 1, page 63), the LEEI value of this starting point to the safety is 0.3.

Such a low LEEI indicates that the space design of the Exit Access region along the route has some problem, which misleads the evacuee away from the most efficient route to the safety. According to the above step analysis, the misleading happens in the early steps. In the first step, the simulated evacuee has already perceived D-03 leading to the most efficient route. However, the Exit door is invisible hidden behind the doorway entrance. In the following several steps, the simulated evacuee does pass by the cue D-03 when he approaches D-02. However, the Exit door is on the opposite direction of his movement. As a result, he misses the most efficient route and evacuates through a route with the low efficiency.

Briefly, in this demonstration, it is shown how the simulated evacuee makes decisions during the route searching process. As a prototype of the computational model, SpaceSensor uses the readable dynamic simulation process to explain how the evacuee searches the route to the safety in the complex public underground space design.

However, to analyze the problems in the space design along a route is one thing. How to find such problematic routes from hundreds of starting points connecting the Occupied Rooms to the Exit Accesses in a huge underground space design is another thing. In the next demonstration, it is introduced how SpaceSensor evaluates the space design to reveal the problematic routes with the criteria LEEI rapidly.

3.6.3 Demonstration on LEEI Evaluation

In this demonstration, SpaceSensor is used to evaluate all the LEEI values for the space design surrounding the doors connecting the Occupied Rooms to the Exit Accesses on B2 level. They are the starting points from SP-01 to SP-21. Notably, the LEEI values are evaluated only for the four leaving points on this level to tell the architects whether the evacuee will use the two exits (E-03 and E-06) and the two stairs (S-02 and S-03) as they plan.

SpaceSensor is setup very similar to the above demonstration except that another 20 starting points are added to the Entrance layer and enable the two options: Same Level Simulation and Batch Simulation for All the Entrances. As a result, 21 routes (Fig.3.6-4) and detailed reports (Table 3.6-7) are generated by SpaceSensor, with which the problematic routes are rapidly found according to the LEEI values from high to low.

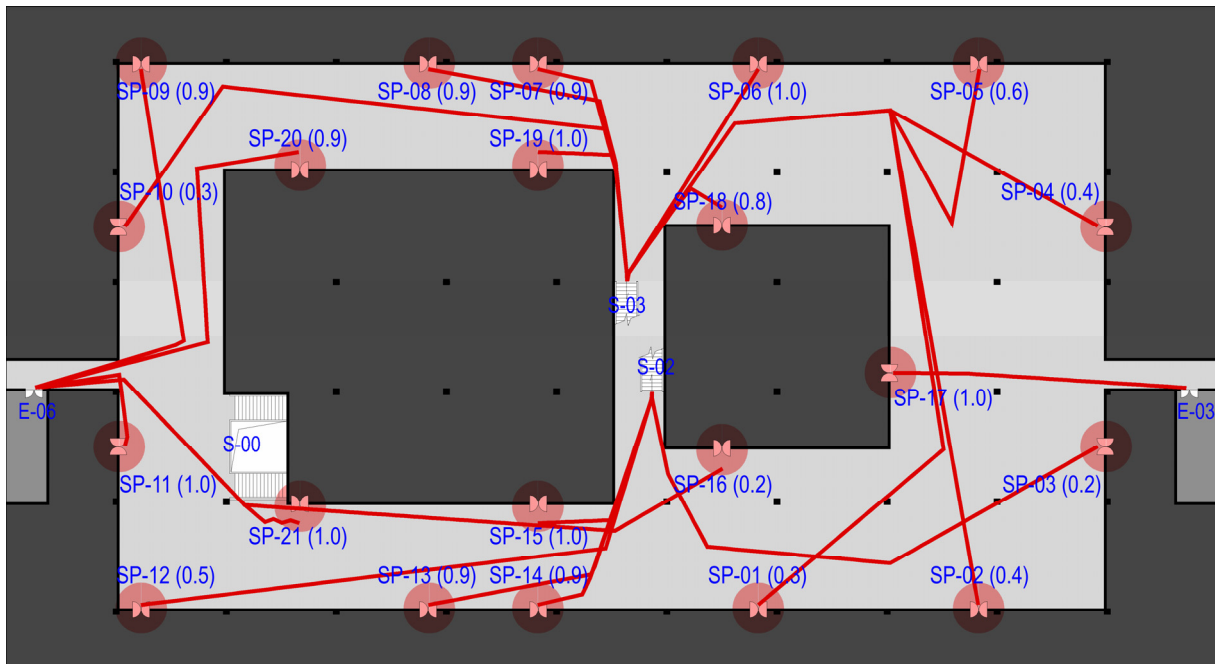


Figure 3.6-4 Plan of B2 level with multi-routes

Table 3.6-7 LEEI report of the multi starting points on B2 level

| Starting Point | Real Leaving Point | Distance of the Simulated Route (meter) | Nearest Leaving Point | Distance of the Shortest Route (meter) | LEEI |
|----------------|--------------------|-----------------------------------------|-----------------------|----------------------------------------|------|
| SP-01 | S-03 | 71.3 | S-02 | 18.4 | 0.3 |
| SP-02 | S-03 | 64.9 | E-03 | 25.4 | 0.4 |
| SP-03 | S-02 | 44.9 | E-03 | 11.0 | 0.2 |
| SP-04 | S-03 | 44.7 | E-03 | 15.9 | 0.4 |
| SP-05 | S-03 | 48.3 | E-03 | 30.0 | 0.6 |
| SP-06 | S-03 | 19.1 | S-03 | 19.1 | 1.0 |
| SP-07 | S-03 | 19.8 | S-03 | 18.3 | 0.9 |
| SP-08 | S-03 | 27.3 | S-03 | 25.0 | 0.9 |
| SP-09 | E-06 | 32.9 | E-06 | 29.5 | 0.9 |
| SP-10 | S-03 | 54.2 | E-06 | 17.3 | 0.3 |
| SP-11 | E-06 | 11.8 | E-06 | 11.8 | 1.0 |
| SP-12 | S-02 | 48.2 | E-06 | 23.0 | 0.5 |
| SP-13 | S-02 | 27.4 | S-02 | 25.4 | 0.9 |
| SP-14 | S-02 | 19.9 | S-02 | 18.8 | 0.9 |
| SP-15 | S-02 | 15.9 | S-02 | 15.4 | 1.0 |
| SP-16 | E-06 | 57.4 | S-02 | 9.3 | 0.2 |
| SP-17 | E-03 | 22.4 | E-03 | 22.4 | 1.0 |
| SP-18 | S-03 | 11.5 | S-03 | 9.7 | 0.8 |
| SP-19 | S-03 | 15.4 | S-03 | 15.4 | 1.0 |
| SP-20 | E-06 | 34.5 | E-06 | 29.6 | 0.9 |
| SP-21 | E-06 | 24.4 | E-06 | 24.4 | 1.0 |

Notes: The starting points in lighter grey don't need further analysis according to the LEEI values.

First, it is noticed that the six starting points (SP-06, SP-11, SP-15, SP-17, SP-19, and SP-21) have LEEI value 1.0, which means that the space along the routes from these points are very well designed offering the proper local architectural cues to induce the evacuee to approach the Nearest Leaving Point just as the architect plans. Thus, it is not necessary to analyze them in detail.

Second, it is noticed that the six starting points (SP-07, SP-08, SP-09, SP-13, SP-14, and SP-20) have LEEI value 0.9. The Real Leaving Point and the Nearest Leaving Point are same in these points. It is believed that the space around these points can also work as the architect plans. Obviously, nobody will walk precisely along the shortest route from one wall corner to the other as the path used by the architect in the evacuation route distance calculation. LEEI value 0.9 is high enough to indicate that the evacuee follows the route planned by the architect. Thus, it is not necessary to analyze them in detail, either.

Third, it is noticed that one starting point (SP-18) has LEEI value 0.8. The same judgment on this point is given as the above points.

Last, it is noticed that the rest starting points have the relative low LEEI values. Furthermore, their Real Leaving Points are different from their Nearest Leaving Points, which means the space along the routes from these starting points can not work as the architect plans. Thus, they are the problematic routes the architect looks for, and they need the further analysis to reveal the problems in the space design just as in the previous demonstration.

Briefly, with the above LEEI-based evaluation process, the architect can rapidly find out the problematic routes in a complex public underground space design, which may contain hundreds of starting points connecting the Occupied Rooms to the Exit Accesses. These problematic routes reflect the misleading effects of the improperly designed local architectural cues along the routes. Just as introduced in the previous demonstration, after the architect find out the problematic routes, he can analyze the log files related to these routes to reveal the problems in his space design.

3.6.4 Conclusions

The computer-based prototype SpaceSensor is developed according to the computational model to achieve the two aims raised in the very beginning of this chapter. In the first demonstration, through the captured artificial visions and offering the log file depicting the whole decision making process along the route, SpaceSensor visually shows how the evacuee searches his route to the safety in the complex public underground space design. Furthermore, in the second demonstration, SpaceSensor helps the architect to evaluate his space design to find out the problematic routes rapidly from a large number of routes in the design according to the criterion LEEI. With these problematic routes revealed, he can analyze the decision process along these routes recorded in the log files to reveal the improper space design just as introduced at the end of the first demonstration.

3.7 Summary of the Chapter

In this chapter, the second research question (*How can such a process based on local architectural cue choice be modeled in an architect-oriented evaluation tool?*) is answered. Two aims are set for this modeling research. On the one hand, the above process must be explained in a computational model with the specific scenario and application context. On the other hand, an architect-oriented criterion LEEI to evaluate the space designs must be supported by the model.

Before explaining the above process in a computational model with the specific scenario and application context, there are still four questions to answer, which are raised in the end of Chapter 2. Thus, the four corresponding steps are used to find answers to these questions and to complete the understanding on this process in a computational way.

First, the questionnaires are used to survey from which architectural elements the evacuees can perceive the local architectural cues in the context of complex public underground space designs. Additionally, from these cues, the most important three local architectural cues are selected for the proposed model.

Second, a CAVE platform is built to observe the virtual evacuation behavior to deduce the knowledge about the cognition rules and the related events of the three local architectural cues.

Third, the computational model framework is composed for the route searching process according to the literature studies in Chapter 2 and the two surveys mentioned above.

Fourth, within the developed framework, the suggested research method in Chapter 2 is used to build the preference prediction function to transit the qualitative conclusions on the local architectural cues to the quantitative variables driving the model.

With the four questions answered, all the components are ready for the computational model to explain the process that the evacuee searches the route to the safety in the complex public underground space design. According to this computational model, a computer-based prototype SpaceSensor is built to achieve the two aims raised in the very beginning. SpaceSensor visually shows how the evacuee searches his route to the safety in the complex public underground space design through the captured artificial visions and the details of the whole decision making process along the route. Furthermore, SpaceSensor supports the criterion LEEI to help the architect in the space design evaluation to find out the problematic routes rapidly.

Finally, with the two aims achieved by SpaceSensor, the second research question is answered. However, at this moment this model has not been validated. The last question at the end of Chapter 2 (*How can the proposed model be validated through indirect evacuation data?*) and the last research question (*How can such a model be validated?*) will be investigated in the next chapter.

4 Validations

In this chapter, the last research question (*How can such a model be validated?*) is answered in two steps after a discussion on the validation method for this specific model. In the first step, the prediction abilities of the proposed model and a model using the *local* nearest-exit assumption are compared with each other referring to the participants' static cue choices observed in the previous experiment (Section 3.5). In the second step, the prediction abilities of the proposed model and a model using the *global* nearest-exit assumption are compared with each other referring to the participants' dynamic cue choices observed in another previous experiment (Section 3.3).

4.1 Discussion on the Validation Method

As argued by Feigenbaum, “Models are our own interpretations of reality.” (qtd. in Ozel, 1987) Thus, an ideal validation of any model should be conducted through the comparison between the prediction from the proposed model and the observation from real world, which are set as a reference in the validation. As a result, the coherence from the prediction to the observation indicates to what extent the model can be validated. However, with the unethical reason mentioned in Section 2.4.1, it is hard to setup real evacuation events in extreme situation according to a systematic plan to directly observe the evacuees’ behavior, which can be used as a direct reference in the validation. Consequently, researchers in this field have to use various kinds of indirect reference to validate their models. In the following, the indirect reference and the comparative method used in the validation for the proposed model is discussed.

4.1.1 Indirect Reference

As mentioned in Section 2.4.1, there are basically two kinds of indirect reference: the indirect reference observed in real-world and the indirect reference observed in laboratory experiment. Either indirect reference has its advantages and disadvantages.

In real-world observation, researchers can collect data from realistic post-facto investigations or fire drills. Although both approaches can provide the most realistic indirect data in the evacuation researches, it is very difficult or sometimes even impossible to use such approaches to deal with the research object with multi variables or isolated variables. Both approaches are greatly limited by the number of real environment samples available. A specific environment sample for multi-variable investigation can be easily out of availability. Meanwhile, the both approaches are greatly limited by the integrated physical appearance of real environments. A specific factor of the environment can’t be investigated without the interference from other factors. In other words, it is hard to isolate any variable.

In laboratory observation, researchers can collect data in represented environment. Although such an approach can provide a complete control on variables of environment through its representation, the reliability and validity of the environmental representation is always a question. However, with booming virtual reality techniques and the excellent control on the environmental representation, many researchers start to use virtual reality systems in their human behavioral experiments especially for researches on multi-variable or abstract research object, which are hardly surveyable through real-world observation (Janzen et al, 2001; Jansen-Osmann & Wiedenbauer, 2004; Cubukcu & Nasar, 2005; Tlauka et al, 2005; Janzen, 2006; Sadeghian et al, 2006; Burigat & Chittaro, 2007; Buxbaum et al, 2007; Jansen-Osmann et al, 2007; Morganti, Carassa, & Geminiani, 2007; Newman et al, 2007; Omer & Goldblatt, 2007; Pazzaglia & Taylor, 2007; Meilinger, Knauff, & Bulthoff, 2008; Spiers & Maguire, 2008).

Notably, sometimes the two kinds of indirect references can act as the complement to each other in the evacuation experiment. For example, Kobes et al (2007) use both the virtual reality system BART and the uninformed fire drill in the evacuation research, which focuses on several environmental factors, such as smoke, exit sign, and etc.

With the consideration on the above approaches to collect indirect reference data, only the indirect reference observed in CAVE-based laboratory experiments is used in the validation of this model. On one hand, the realistic appearance of the environment in fire drill can’t isolate the abstract

research object (the geometric features of the local architectural cues) in a feasible way, and a few environment samples can't support the systematic investigation on the multi variables. On the other hand, the CAVE platform can provide an abstract representation of the environment for the research object in a recognizable way, and it is easy to generate enough environment samples digitally for multi variables.

Besides the choice on the observation method for the indirect reference, the choice of the observation resolution for the indirect reference is another issue in the validation. There are at least three kinds of resolutions. At a micro resolution, the vectors along the evacuee's trajectory should be completely observed. The models simulating the individual's exact movement in every step, such as Helbing et al's (2000) social force model, needs such a reference in the validation. At a middle resolution, the evacuee's choices at decision points along its route should be observed. The models simulating the evacuee's decision process rather than the exact movement of every step, such as Raubal and Worboys' (1999) "Clue-Choice" model, needs such a reference. At a macro resolution, the occupancy or density of the evacuees in rooms should be observed. The models simulating the reduction process of evacuees in every room, such as ALLSAFE (Kuligowski & Peacock, 2005), needs such a reference. With the focus on the evacuee's local architectural cue choices along the route to the safety rather than the exact movement in every step, the thesis uses the middle resolution for its indirect reference in the validation.

In brief, the thesis uses indirect reference observed in the virtual evacuation experiments at a middle resolution for the validation. One is the participants' static paired choices observed in the experiment introduced in Section 3.5. The other is the participants' dynamic local architectural cue choices reflected by the trajectories observed in the experiment introduced in Section 3.3.

4.1.2 Comparative Method in Validation

Following Feigenbaum's argument "Models are our own interpretations of reality." (qtd. in Ozel, 1987), the validation holds a view that any model as a subjective interpretation of ideal reality can only provide incomplete prediction capability. Thus, being always incomplete, the extent of the coherence between the model and the reference is not the only important issue in the validation. An ideal validation should also indicate whether there is an improvement in the proposed model from others. In other words, it should indicate whether the proposed model contributes to our interpretation of the reality. From such a view, the thesis uses the comparative method to validate the proposed model referring to not only the selected indirect references but also the prediction capabilities of other models. There are two levels of these comparisons in the validation (Fig.4.1-1).

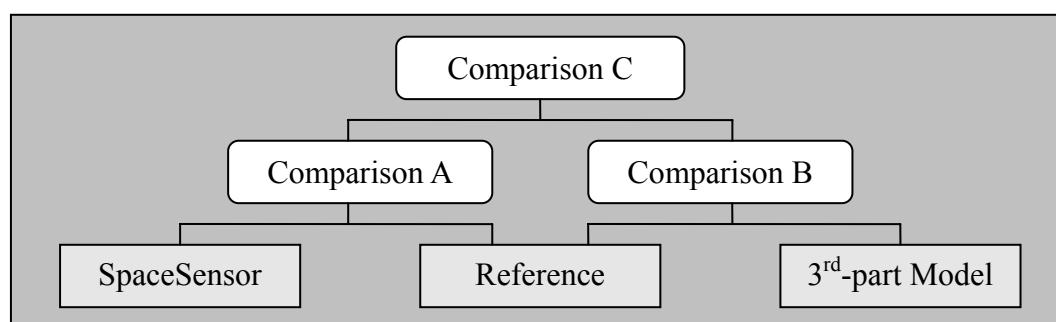


Figure 4.1-1 Two levels of comparisons in validation

The lower level contains Comparison A & B, which share the same reference. According to the coherence to the reference, either the proposed model SpaceSensor or the selected 3rd-party model

Architectural Cue Model in Evacuation Simulation for Underground Space Design

gets a score indicating its prediction capability (degree of validity) on the cue choice. In the first validation, the “Overall Predicted Correction Percentage” of the cue choice is used as the indicator. The participants’ static paired choices observed from the experiment in Section 3.5 are regarded as the indirect reference with the ideal 100% correct prediction capability. In the second validation, the percentage of correctly predicted routes is used as the indicator. The participants’ dynamic cue choices along the trajectories observed from the experiment in Section 3.3 are regarded as the indirect reference with the ideal 100% correct prediction capability.

Based on Comparison A & B, a higher level Comparison C is conducted between the two values of the indicator from the previous two comparisons. With the same reference as a benchmark, Comparison C can indicate whether there is an improvement of the prediction capability (degree of validity) in the proposed model from the 3rd-party model.

In brief, the thesis uses a set of comparisons at different levels not only to validate the proposed model according to the indirect reference but also to indicate the improvement of the cue choice prediction capability from the existing models.

4.2 Comparing with the Local Nearest-exit Model

Referring to the choice data collected in the estimation experiment (Section 3.3), the prediction capabilities of the proposed model and a model using the local nearest-exit assumption are scored and compared. As introduced in Chapter 2, there is a general category of the evacuation models called “Local Architectural Cue Supported” model (Table 2.3-1), in which the simulated evacuee has an artificial vision and searches his route to the safety according to his visual perception on local architectural elements. As the latest representatives of this category, the models EVACSIM, MASSegress, and SGEM in a branch called “Conditional Nearest-Exit Approaching” share the assumption that the evacuee will always approach the nearest exit perceived locally with some other conditions, such as the smoke situation or designated familiarity. According to the introduction in Chapter 2 about the several information sources of the local architectural cue and the conclusion in the observation experiment about the non-distance attribute influencing the route searching, it is hypothesized that the proposed model covering seven attributes of the architectural element should have the better prediction capability than such a kind of models with only the distance attribute supporting the local nearest-exit assumption. To prove this hypothesis and to examine if the proposed model does show the improvement, a model with only the distance attribute is used in the comparison.

First, the choice data collected from the estimation experiment is transformed for this comparison. The original data in one row representing the two cues of a profile (e.g. Table 3.5-11) is split into two rows. The columns “Chosen” and “RatioD” are kept, and the others are removed. The seven levels of the distance attribute RatioD are encoded into two levels (0 as “close”, 1 as “far”) according to the encoding plan (Table 4.2-1). Notably, when the level is 4, the two cues with the same distance, the both cues are encoded to 1, which means the choice probability will be calculated as fifty to fifty with one cue chosen and the other not chosen.

Next, as a mathematic model supporting the local nearest-exit assumption, a simplified preference prediction function with only the distance attribute (Eq. 3) is built on these encoded choices. Notably, this function is to predict the probability of a cue (not only the left one) being chosen in a cue pair.

Table 4.2-1 Encoding plan for distance attribute

| Levels of RatioD | Values (L : R) | New Level of Left Cue | New Level of Right Cue |
|------------------|----------------|-----------------------|------------------------|
| 1 | 1 : 8 | 0 | 1 |
| 2 | 1 : 4 | 0 | 1 |
| 3 | 1 : 2 | 0 | 1 |
| 4 | 1 : 1 | 1 | 1 |
| 5 | 2 : 1 | 1 | 0 |
| 6 | 4 : 1 | 1 | 0 |
| 7 | 8 : 1 | 1 | 0 |

Notes: **L**: left cue; **R**: right cue

$$p(c) = \frac{e^{z_{picked}}}{e^{z_{picked}} + e^{z_{unpicked}}} \quad (3)$$

Where:

$p(c)$ is the probability of a cue being chosen in the cue pair;

$$Z_{picked} = \beta_0 + \beta_{RatioD} X_{RatioD}$$

$Z_{unpicked} = 0$ (The reference alternative in the choice set.)

β_0 is the B value of the intercept.

β_{RatioD} is the B value of a specific variable level for RatioD.

X_{RatioD} is the dummy variable for the RatioD. When the reference level of the variable is input, the dummy variable will be 0. With the other level, it is 1.

Finally, all the B values for this function (Appendix F) are estimated and the prediction capabilities of the proposed model and this model (Table 4.2-2) are compared with each other according to McFadden’s R^2 and Overall Predicted Correction Percentage. Obviously, the proposed model always indicates the better prediction capability than the model with the local nearest-exit assumption.

Table 4.2-2 Overview of the comparison between SpaceSensor and the local nearest-exit model

| Cue Pair Type | McFadden’s R^2 | | Overall Predicted Correction Percentage | |
|---------------|--------------------------|-------------|-----------------------------------------|-------------|
| | Local Nearest-Exit Model | SpaceSensor | Local Nearest-Exit Model | SpaceSensor |
| D-D | 0.026 | 0.105 | 59.4% | 65.1% |
| S-E | 0.073 | 0.149 | 65.7% | 69.2% |
| S-S | 0.086 | 0.209 | 66.9% | 71.8% |
| E-E | 0.105 | 0.220 | 68.6% | 73.5% |

In summary, according to the above comparison, the proposed model does indicate an improvement from the “Conditional Nearest-Exit Approaching” models. It proves the hypothesis in the very beginning of this comparison. It also supports the introduction in Chapter 2 about the several information sources of the local architectural cue and the conclusion in the observation experiment about the non-distance attribute influencing the route searching. Furthermore, in the research context, the prediction capability of the model in “Random Exit Searching” branch is almost fifty percent in a large number of choices between two cues, and the prediction ability of the model in “Preference Level Following” branch greatly depends on the (un)reliable system operator’s input. Thus, the models in both branches do not perform better than the proposed model, either. As a result, it is concluded that the proposed model indicates a certain degree of validity and more importantly an improvement from the models in “Local Architectural Cue Supported” category in the research context.

4.3 Comparing with the Global Nearest-exit Model

Referring to the evacuation routes from the fourteen starting points collected in the observation experiment, the prediction capabilities of the proposed model and the model using the global nearest-exit assumption are scored and compared. As introduced in Chapter 2, the other general category of the evacuation models is “Global Architectural Cue Supported” models (Table 2.3-1), in which the simulated evacuee explicitly or implicitly has the knowledge about the whole space and always goes to the global nearest exit. As indicated in the classification, most evacuation simulation models belong to this category. As one of such models, Simulex is often used to compare with other evacuation simulation models in validation researches, such as the research on MASSegress (Pan, 2006), the research on EXIT89 (Kuligowski, 2003), and the research on ASERI, buildingEXODUS, and PedGo (Rogsch, Seyfried, & Klingsch, 2005). It is used as the representative of the models with the global nearest-exit assumption in this comparison. According to the discussion in Chapter 2 that the evacuee can only depend on the local architectural cues rather the global ones in this research context, it is hypothesized that the proposed model should have a better prediction capability than Simulex in such a context. To prove this hypothesis and to examine if the proposed model does show the improvement, the prediction capabilities of SpaceSensor and Simulex are compared referring to the dynamically collected routes in the observation experiment.

4.3.1 Overview

First, the reference data are prepared. Three kinds of information are extracted from every starting point in the observation experiment. They are: the total number of the terminations chosen by the participants, the percentage of the participants in the most preferred termination, and the termination chosen by the most participants. Notably, among all the traces from every starting point, the main route shared by the most participants is used to do the comparison.

Next, both SpaceSensor and Simulex in Virtual Environment v5.8 are used to simulate the evacuation routes in the same three-story underground space from the same fourteen starting points as used in the observation experiment. SpaceSensor is set with the default options and works just as introduced in Section 3.6. Simulex uses a “Distance Map” to drive the simulated evacuee. Every cell of this map stores the distance to the global nearest exit. The simulated evacuee always selects the cell with the minimum distance next to the current cell to approach the global nearest exit.

Finally, an overview of the comparison between SpaceSensor and Simulex are created referring to the evacuation routes collected in the observation experiment (Table 4.3-1). Obviously, the prediction ability of SpaceSensor (92.9% correction) is much better than Simulex (28.6% correction). The only wrongly predicted route from Starting Point V by SpaceSensor involves a much more dispersive set of terminations chosen by the participants, which is indicated by the most “Number of the Chosen Terminations” and the least “Participant Percentage in the Most Preferred Termination”. It suggests that the proposed model can’t predict the route choice correctly when the real persons don’t have an obvious propensity in the route choice. Obviously, it is reasonable.

In the following, these simulated routes are analyzed one by one to have an inside look at the basic difference between the two models, although sometimes they predict the same route.

Table 4.3-1 Overview of the comparison between SpaceSensor and Simulex

| Starting Point | Reference Routes | | | Prediction by SpaceSensor | Prediction by Simulex |
|----------------|-----------------------------------|----------------------------------------------------------|-------------|---------------------------|-----------------------|
| | Number of the Chosen Terminations | Participant Percentage in the Most Preferred Termination | Termination | | |
| I | 5 | 44.1% | Exit C | Correct | Wrong |
| II | 3 | 65.2% | Exit C | Correct | Correct |
| III | 5 | 65.4% | Stair A | Correct | Wrong |
| IV | 4 | 80.5% | Stair A | Correct | Wrong |
| V | 13 | 25.4% | Exit G | Wrong | Wrong |
| VI | 9 | 27.1% | Exit B | Correct | Wrong |
| VII | 3 | 80.8% | Stair A | Correct | Wrong |
| VIII | 2 | 92.4% | Exit A | Correct | Correct |
| IX | 3 | 82.7% | Stair A | Correct | Correct |
| X | 3 | 94.1% | Exit B | Correct | Correct |
| XI | 2 | 90.4% | Stair A | Correct | Wrong |
| XII | 3 | 83.9% | Exit B | Correct | Wrong |
| XIII | 3 | 86.6% | Stair A | Correct | Wrong |
| XIV | 2 | 68.6% | Stair A | Correct | Wrong |

4.3.2 Analysis

Both simulated routes on the underground site plans are presented in overlay upon the floor plan for every starting point. The route predicted by SpaceSensor is in a solid line. The route predicted by Simulex is in a dash line. No matter whether the route is predicted correctly or wrongly, the mechanisms behind the route in the two models are analyzed to reveal the totally different ideas behind them.

1) Predictions for Starting Point I

From Starting Point I, SpaceSensor makes the correct prediction on the evacuation route to Exit C, while Simulex makes the wrong prediction on the evacuation route to Exit E (Fig.4.3-1). Exit E is the global nearest exit to the starting point. Simulex assumes that the evacuee knows it and uses it for certain. However, the simulated evacuee in SpaceSensor can't visually perceive it hidden behind the parking coaches. He is attracted by the big Doorway Entrance in front of him and ignores Stair A and Exit D on the two sides out of his limited vision. With the further Doorway Entrances perceived on his right side, he turns right. At that moment, he visually perceives Exit C and chooses it as the goal.

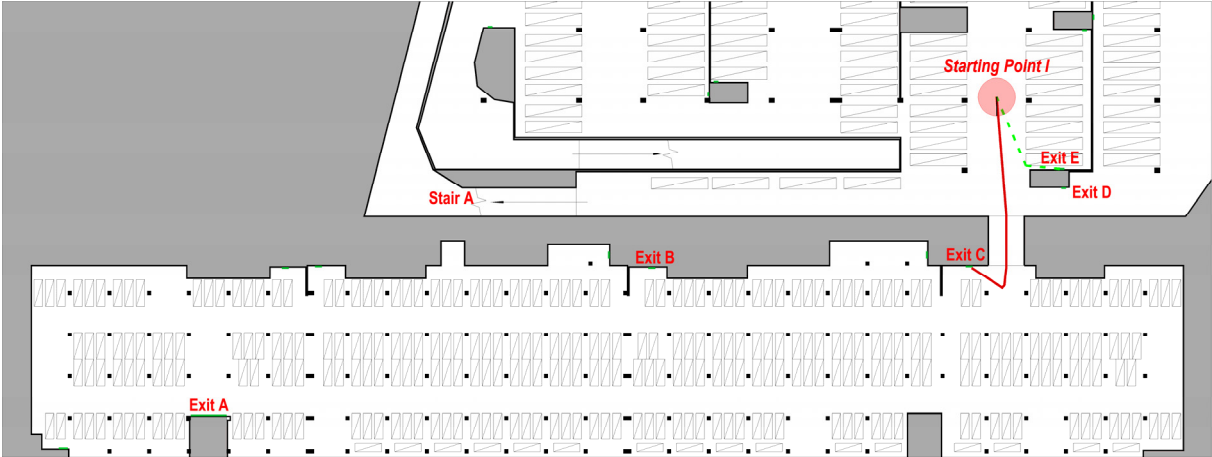


Figure 4.3-1 Simulated traces from Starting Point I

2) Predictions for Starting Point II

From Starting Point II, both SpaceSensor and Simulex make the correct prediction on the evacuation route to Exit C (Fig.4.3-2). However, the predictions are driven by different mechanisms. Exit C is the global nearest exit to the starting point. Simulex assumes that the evacuee uses it for certain. The simulated evacuee in SpaceSensor doesn't know it. He chooses Exit C after he perceives it and prefers it rather than Exit A according to their different attributes.



Figure 4.3-2 Simulated traces from Starting Point II

3) Predictions for Starting Point III

From Starting Point III, SpaceSensor makes the correct prediction on the evacuation route to Stair A, while Simulex makes the wrong prediction on the evacuation route to Exit C (Fig.4.3-3). Exit C is one of the global nearest exit to the starting point. Simulex assumes that the evacuee knows it and uses it for certain. However, the simulated evacuee in SpaceSensor can't visually perceive it on the opposite of the egress direction. He is attracted by the big Doorway Entrance D first. After heading Doorway D for several steps, he perceives Stair A. He chooses Stair A rather than Exit D or any further stairs, such as Stair B according to their attributes.

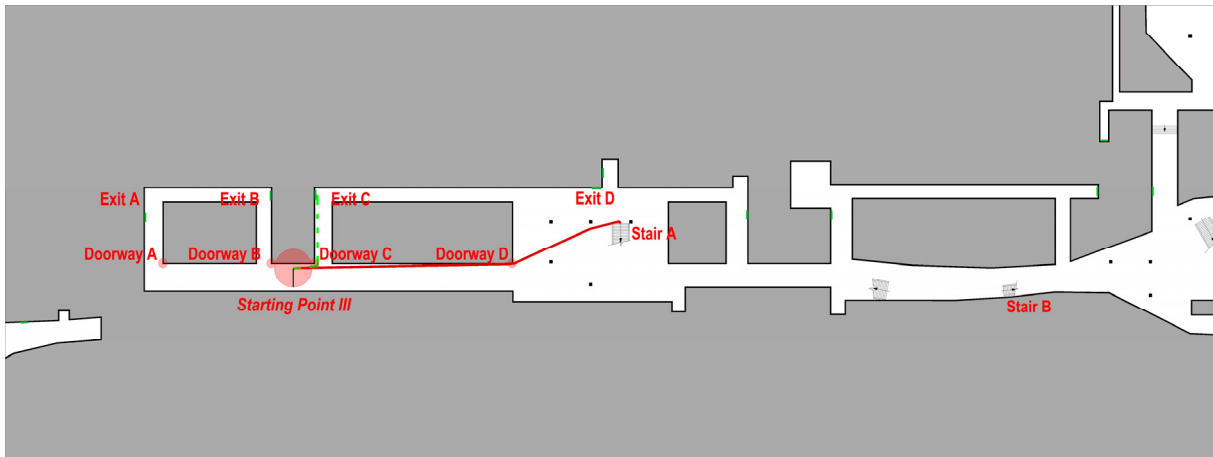


Figure 4.3-3 Simulated traces from Starting Point III

4) Predictions for Starting Point IV

From Starting Point IV, SpaceSensor makes the correct prediction on the evacuation route to Stair A, while Simulex makes the wrong prediction on the evacuation route to Exit A (Fig.4.3-4). Exit A is the global nearest exit to the starting point. Simulex assumes that the evacuee knows it and uses it for certain. However, the simulated evacuee in SpaceSensor can't visually perceive it hidden behind Doorway A. He first chooses the wider Stair A rather than Stair B. When he turns to Stair A and perceives Doorway A, he still prefers Stair A rather than Doorway A. Such a decision makes him miss the global nearest-exit Exit A.

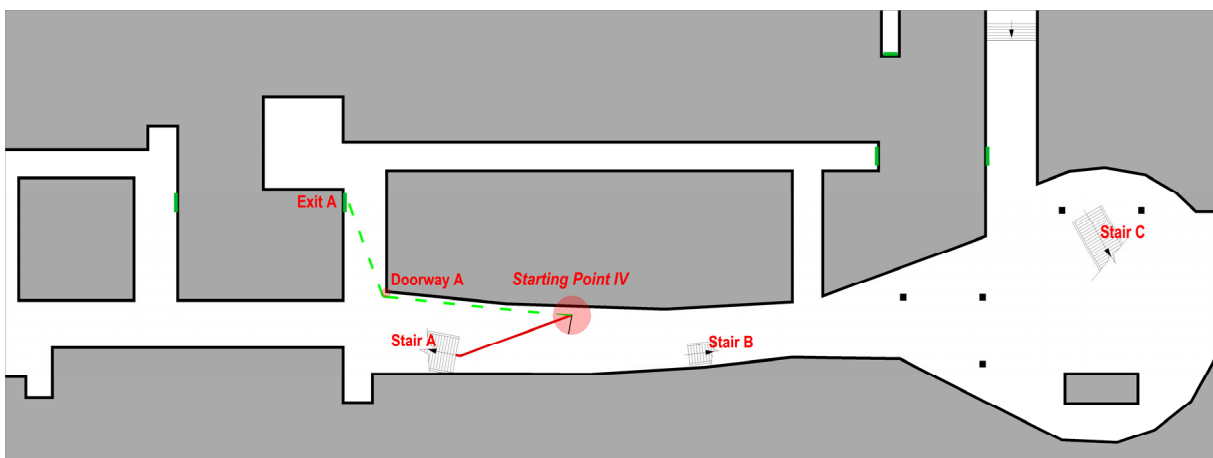


Figure 4.3-4 Simulated traces from Starting Point IV

5) Predictions for Starting Point V

From Starting Point V, either SpaceSensor or Simulex makes the wrong prediction on the evacuation route to Exit D (Fig.4.3-5). However, the two wrong predictions are driven by different mechanisms. Exit D is the global nearest exit to the starting point. Simulex assumes that the evacuee knows it and uses it for certain. The simulated evacuee in SpaceSensor doesn't know it. He first turns left for the closer and wider Doorway Entrance. After he turns, the A1 and A2 attributes change, which makes him to choose the very close Doorway Entrance on the right side and follow it to Exit D with the forgetting mechanism.

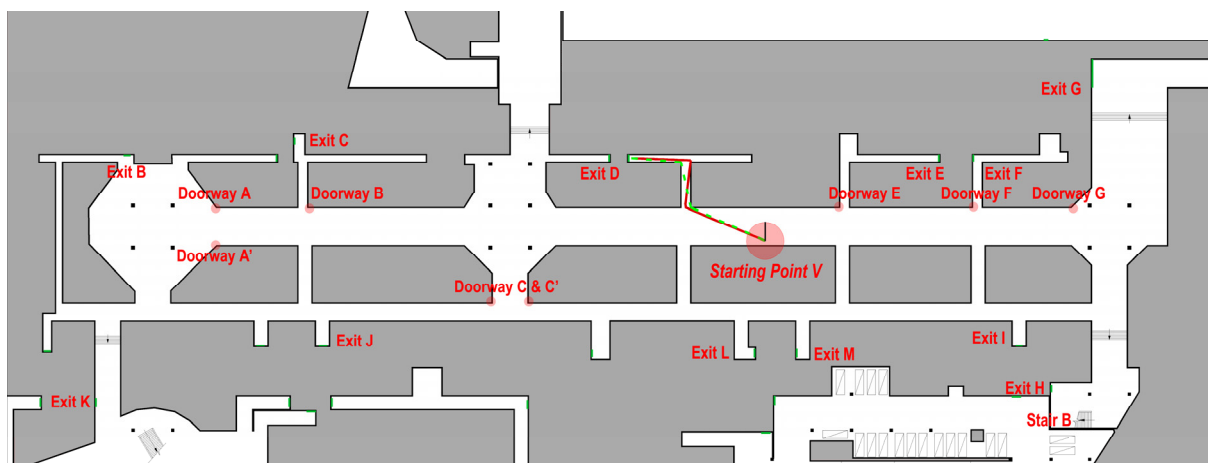


Figure 4.3-5 Simulated traces from Starting Point V

6) Predictions for Starting Point VI

From Starting Point VI, SpaceSensor makes the correct prediction on the evacuation route to Exit B, while Simulex makes the wrong prediction on the evacuation route to Exit D (Fig.4.3-6). Exit D is the global nearest exit to the starting point. Simulex assumes that the evacuee knows it and uses it for certain. However, the simulated evacuee in SpaceSensor can't visually perceive it hidden behind the Doorway Entrance. He chooses Exit B facing his egress direction during his exploration for the Doorway Entrances on the right side.

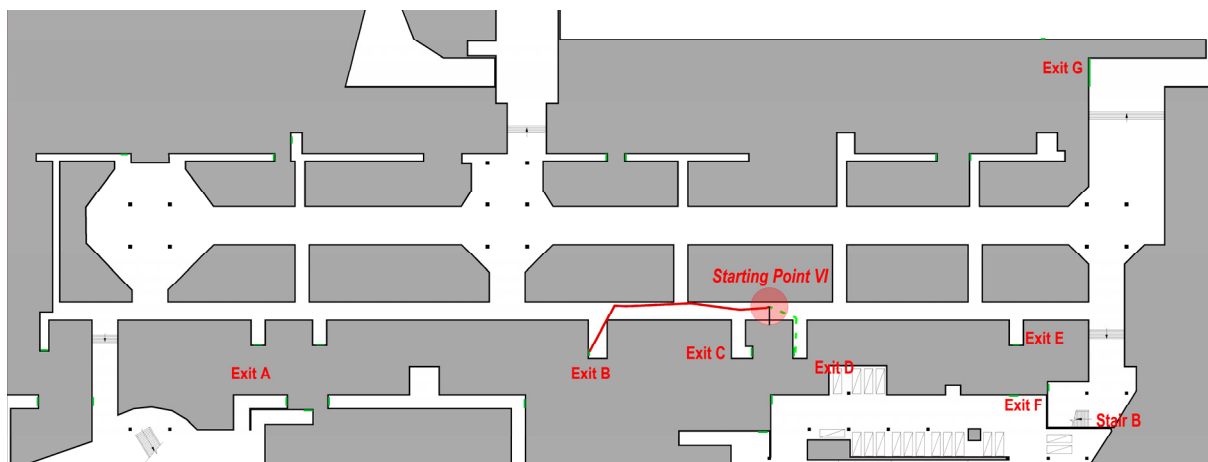


Figure 4.3-6 Simulated traces from Starting Point VI

7) Predictions for Starting Point VII

From Starting Point VII, SpaceSensor makes the correct prediction on the evacuation route to Stair A, while Simulex makes the wrong prediction on the evacuation route to Exit C (Fig.4.3-7). Exit C is the global nearest exit to the starting point. Simulex assumes that the evacuee knows it and uses it for certain. However, the simulated evacuee in SpaceSensor can't visually perceive it out of its limited view field. He is attracted by Stair A rather than the other cues, such as Exit A, Exit B, or Stair B, according to their attributes.

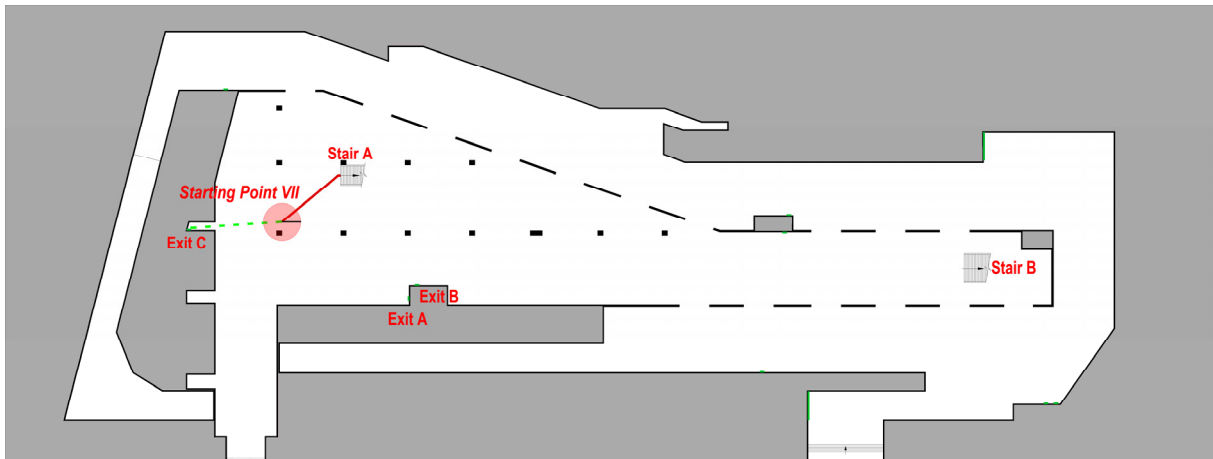


Figure 4.3-7 Simulated traces from Starting Point VII

8) Predictions for Starting Point VIII

From Starting Point VIII, both SpaceSensor and Simulex make the correct prediction on the evacuation route to Exit A (Fig.4.3-8). However, the predictions are driven by different mechanisms. Exit A is the global nearest exit to the starting point. Simulex assumes that the evacuee uses it for certain. The simulated evacuee in SpaceSensor doesn't know it. He chooses Exit A rather than Doorway A according their different attributes.

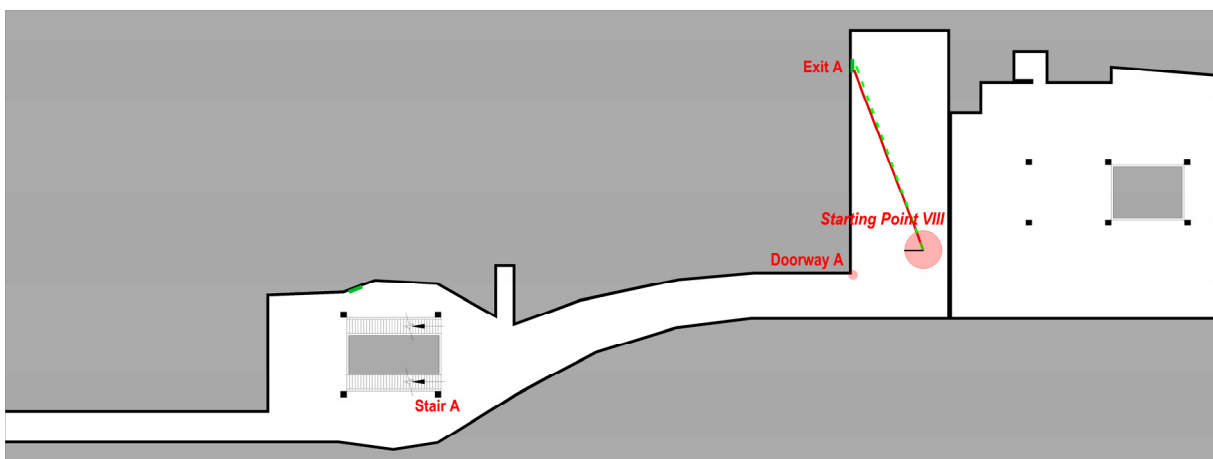


Figure 4.3-8 Simulated traces from Starting Point VIII

9) Predictions for Starting Point IX

From Starting Point IX, both SpaceSensor and Simulex make the correct prediction on the evacuation route to Stair A (Fig.4.3-9). However, the predictions are driven by different mechanisms. Stair A is the global nearest exit to the starting point. Simulex assumes that the evacuee uses it for certain. The simulated evacuee in SpaceSensor doesn't know it. He chooses Stair A rather than the other cues, such as Doorway A, Exit A, or Stair B according their different attributes.

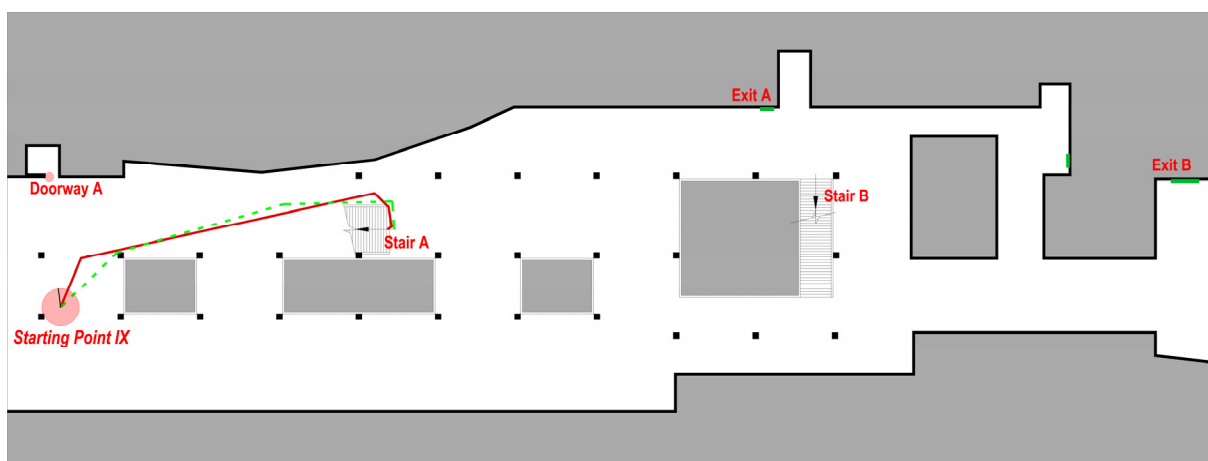


Figure 4.3-9 Simulated traces from Starting Point IX

10) Predictions for Starting Point X

From Starting Point X, both SpaceSensor and Simulex make the correct prediction on the evacuation route to Exit B (Fig.4.3-10). However, the predictions are driven by different mechanisms. Exit B is the global nearest exit to the starting point. Simulex assumes that the evacuee uses it for certain. The simulated evacuee in SpaceSensor doesn't know it. He chooses Exit B rather than the other cues, such as Exit A or Exit C according their different attributes. Meanwhile, with the memory mechanism, he takes a round to reach Exit B although he can't perceive it for a while during the egress.

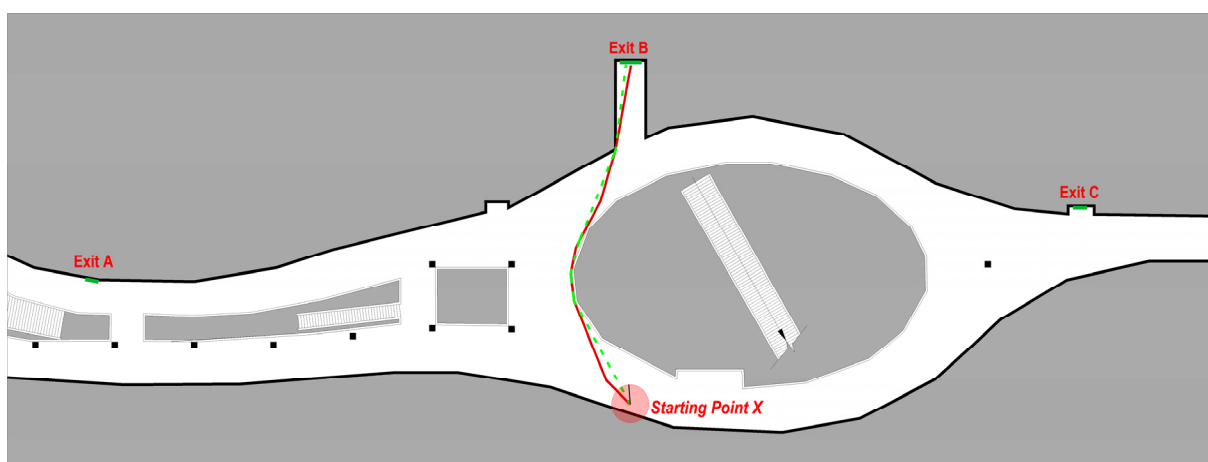


Figure 4.3-10 Simulated traces from Starting Point X

11) Predictions for Starting Point XI

From Starting Point XI, SpaceSensor makes the correct prediction on the evacuation route to Stair A, while Simulex makes the wrong prediction on the evacuation route to Exit A (Fig.4.3-11). Exit A is the global nearest exit to the starting point. (The route to Stair A is just a little bit longer than the route to Exit A, when the stair steps are included in the length of the route by Simulex.) Simulex assumes that the evacuee uses it for certain. However, the simulated evacuee in SpaceSensor prefers Stair A rather than Exit A according to their attributes.

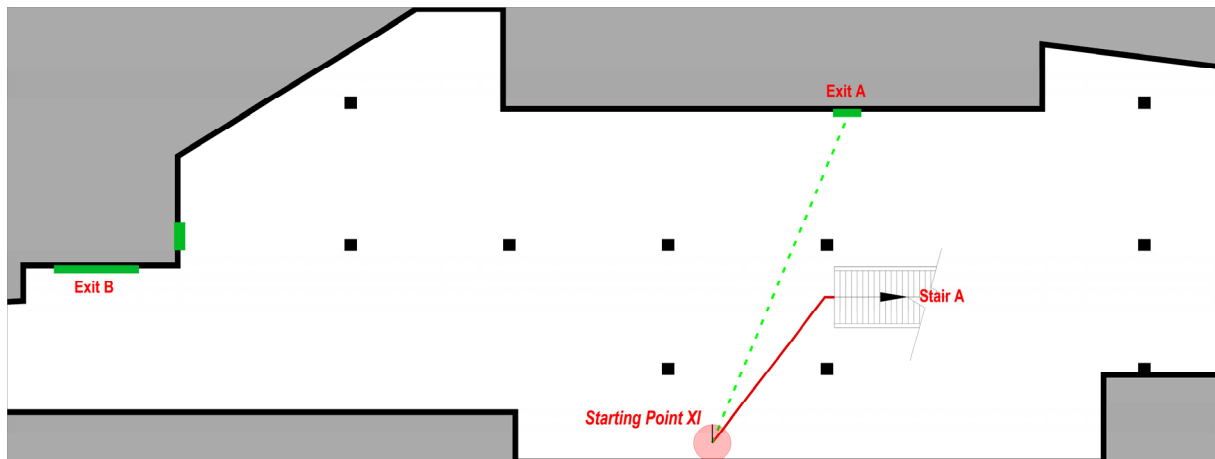


Figure 4.3-11 Simulated traces from Starting Point XI

12) Predictions for Starting Point XII

From Starting Point XII, SpaceSensor makes the correct prediction on the evacuation route to Exit B, while Simulex makes the wrong prediction on the evacuation route to Exit A (Fig.4.3-12). Exit A is the global nearest exit to the starting point. Simulex assumes that the evacuee uses it for certain. However, the simulated evacuee in SpaceSensor prefers the wider Exit B rather than Exit A according to their attributes.

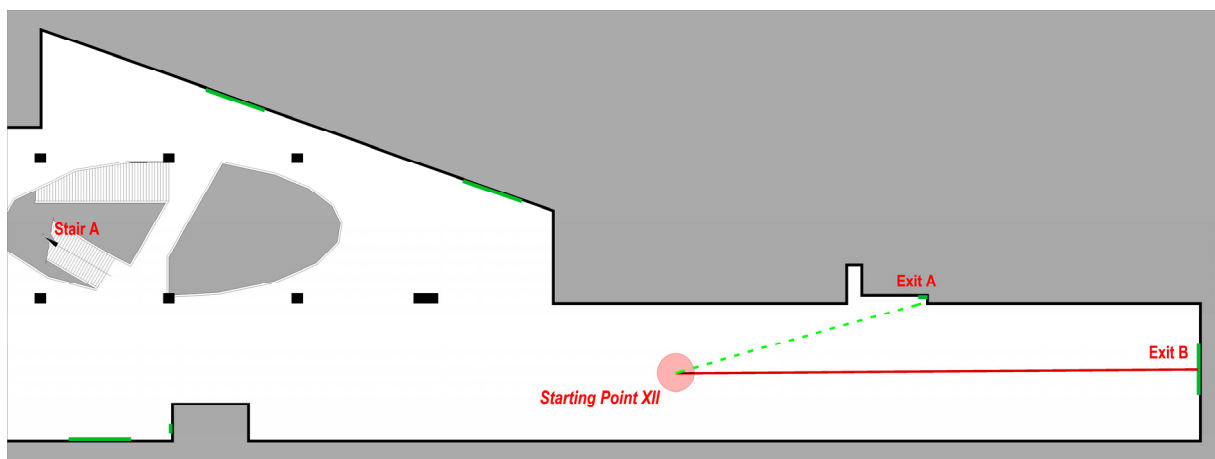


Figure 4.3-12 Simulated traces from Starting Point XII

13) Predictions for Starting Point XIII

From Starting Point XIII, SpaceSensor makes the correct prediction on the evacuation route to Stair A, while Simulex makes the wrong prediction on the evacuation route to Exit C (Fig.4.3-13). Exit C is the global nearest exit to the starting point. Simulex assumes that the evacuee knows it and uses it for certain. However, the simulated evacuee in SpaceSensor can't visually perceive it on the opposite of the egress direction. He prefers Stair A rather than the other cues according to their attributes.

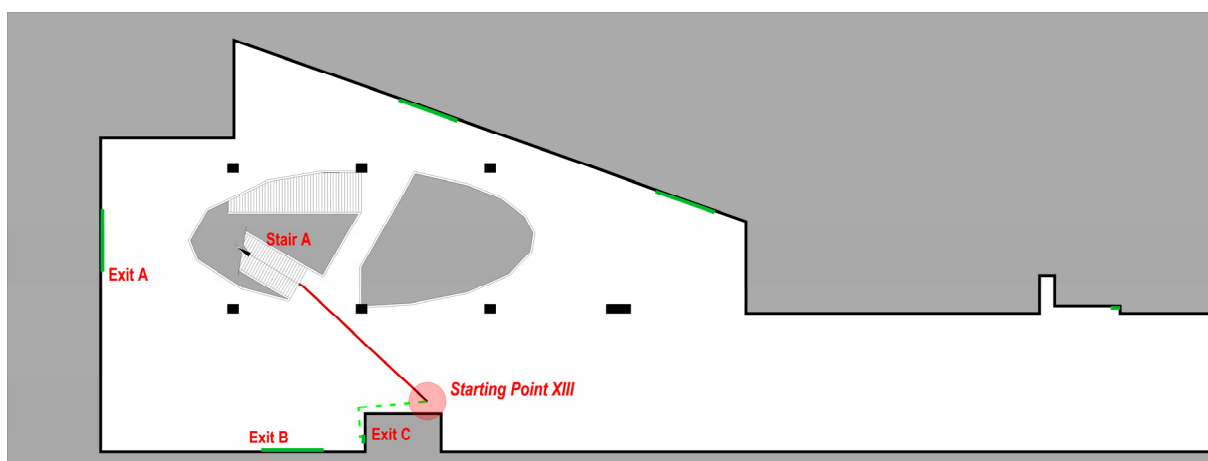


Figure 4.3-13 Simulated traces from Starting Point XIII

14) Predictions for Starting Point XIV

From Starting Point XIV, SpaceSensor makes the correct prediction on the evacuation route to Stair A, while Simulex makes the wrong prediction on the evacuation route to Exit A (Fig.4.3-14). Exit A is the global nearest exit to the starting point. Simulex assumes that the evacuee uses it for certain. However, the simulated evacuee in SpaceSensor prefers Stair A rather than Exit A according to their attributes.

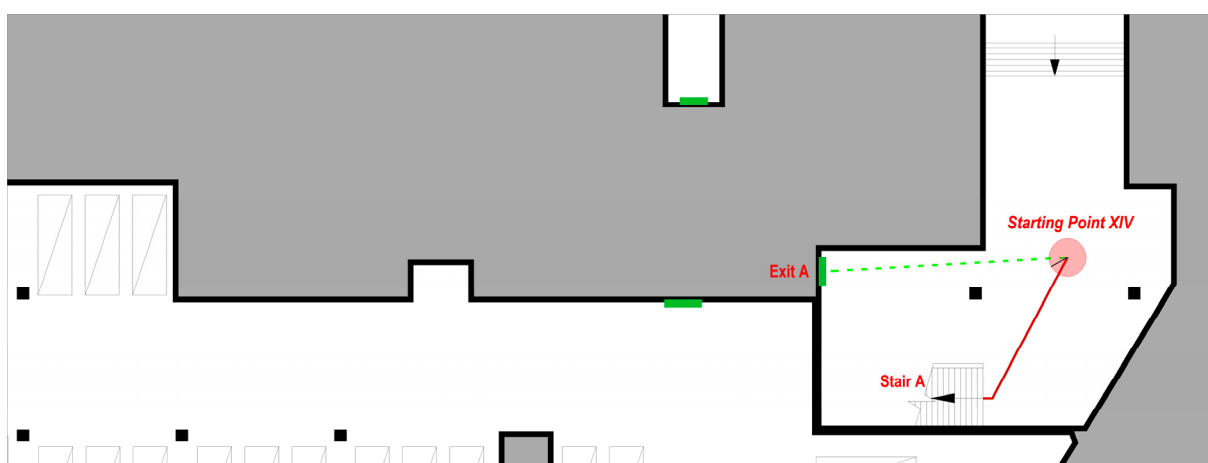


Figure 4.3-14 Simulated traces from Starting Point XIV.

4.3.3 Conclusions

According to the above comparison, it is concluded that the proposed model does indicate a certain degree of validity and more importantly an improvement from the models in “Global Architectural Cue Supported” category represented by Simulex in the research context. It proves the hypothesis in the very beginning of this comparison. With the totally different mechanism behind the two models, it also supports the discussion in Chapter 2 that the evacuee can only depend on the local architectural cues rather the global ones in the research context.

4.4 Summary of the Chapter

In this chapter, the last research question (*How can such a model be validated?*) is answered. Considering the last question (*How can the proposed model be validated through indirect evacuation data?*) at the end of Chapter 2, the validation method including the usage of indirect reference and the comparison method are firstly discussed. Following it, two steps with two sets of indirect references are used in the sets of comparisons to indicate not only the validity of the proposed model but also the improvement of the proposed model from the others.

In the first step, it is shown that in this research context SpaceSensor has the better prediction capability than the models in the *Local Architectural Cue Supported* category through the comparison referring to the static choice data collected in the estimation experiment in the CAVE platform.

In the next step, it is shown that in this research context SpaceSensor has the better prediction capability than the models in the *Global Architectural Cue Supported* category through the comparison referring to the routes dynamically collected in the observation experiment in the CAVE platform.

As a result, according to the validity and the prediction capability improvement indicated in the two steps, the proposed model proves not only valid but also better than the models in the both general categories to explain and simulate the process that the evacuee searches his route to the safety in the complex public underground space design.

5 Conclusions

In this chapter, first this research on the architectural cue model for evacuation simulation in complex public underground spaces is summarized. Afterwards, according to the research result, the three guidelines for the architectural space design of complex public underground environment are suggested. Finally, the thesis is ended with the future directions for this research.

5.1 Summaries of the Thesis

The motivation of this research is to build an architect-oriented computational model to support the evacuation evaluation on complex public underground space design. From such a view, the space design of a complex public underground environment, as the fundamental part of the whole design process and the main part of the architect's work, is regarded as the research context in this thesis. Thus, to improve the performance-based evaluation, the process of the evacuee searching his route to the safety according to the space design has to be understood clearly and to be explained in a computational model. To achieve these, this thesis investigated the following three research questions:

- 1) How does the space design of complex public underground environment influence evacuee's route searching process?
- 2) How can such a process based on local architectural cue choice be modeled in an architect-oriented evaluation tool?
- 3) How can such a model be validated?

To answer the first research question, literatures of the way-finding theories were studied. As a special way-finding process, the route searching behavior in the evacuation was investigated in this research context. It was found that the evacuee searches his route to the safety in a stepwise process. In every step, he behaves in three phases. First, he scans the local architectural cues in his view. Next, he chooses the cue with the highest possibility leading to the safety by his estimation. Last, he moves to the direction hinted by the chosen cue. Besides the understanding of this process, also the potential problems were found in 36 existing evacuation simulation models. According to the environmental psychology research methods, a method was suggested supported by CAVE-based Conjoint Analysis approach for this research to model the described process.

To answer the second research question, a computational model of the route searching process was built in this research context with the new criterion LEEI for the architect to evaluate the space designs. As mentioned in the literature studies, there are still several further questions to answer before the process can be implemented in a computational model. Therefore, the questions were explored step by step. First, questionnaires were used to survey from which architectural elements the evacuees can perceive the local architectural cues in the research context. Second, a CAVE platform was built to observe the virtual evacuation behavior to deduce the knowledge about the cognition rules and the related events of the three local architectural cues. Third, the computational model framework for the route searching process was developed according to the conclusions derived in the literature studies and the two previous surveys. Fourth, the suggested CAVE-based Conjoint Analysis approach was used to build the preference prediction function to transit the qualitative conclusions on the local architectural cues to the quantitative variables driving the model. Finally, with all the above four questions answered, the route searching process can be implemented in a computational model. To demonstrate this model, a computer-based prototype named SpaceSensor was built. On the one hand, it was demonstrated visually how the evacuee searches his route to the safety in the complex public underground space design through the captured artificial visions and the details of the whole decision making process along the route. On the other hand, it was demonstrated that with the aide of the criterion LEEI, the architect can evaluate his design of the complex public underground space to reveal potential problems.

To answer the last research question, two sets of indirect evacuation data were used to validate the proposed model. Through the comparison referring to the static choice data collected in the estimation experiment on the CAVE platform, it was shown that proposed computational model has the better prediction ability than the models in the *Local Architectural Cue Supported* category in

this research context. Meanwhile, through the comparison referring to the routes dynamically collected in the observation experiment on the CAVE platform, it was shown that the proposed computational model has the better prediction ability than the models in the *Global Architectural Cue Supported* category. Concluding, according to the indicated improvement from the models in the both evacuation simulation categories, the proposed computational model is valid and better than the other models in this specific research context.

In summary, this research results in a valid computational model. This model contributes to the architect's evaluation on the space design of the complex public underground environment through the simulation of the route searching process and the calculation of the architect-oriented criterion LEEI. Furthermore, with all the details in the route searching process explained quantitatively, this model also contributes to the architect's understanding on how his design works. Such a new understanding on how the space design works must lead to some new guidelines in the space design, which are discussed in the following.

5.2 Discussions on the New Design Guidelines

According to the computational model, there are at least three guidelines useful in the complex public underground space designs. The first two are about the visual accessibility. The third is about the psychological scale.

5.2.1 Visual Accessibility & Distance Accessibility

As revealed in the computational model, whether the evacuee uses an exit or stair first depends on whether he has the visual accessibility to it. However, the current building codes imply the direct access to the nearest exit, which only depends on the distance accessibility (British Standards Institution, 1997; Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2003; International Code Council, 2006).

As demonstrated in Section 3.6.2, with the improper space design the real evacuation route can be totally different from the planned route with the shortest distance accessibility. If the route is different, it takes more time and gets more potential problems, such as the overload of the other evacuation facilities. In one word, the real evacuation can only become worse than the optimized design. Such a consideration is also supported by several validation reports (Kuligowski & Peacock, 2005; Hostikka et al., 2007) introduced in Section 2.3.2 about the difference between the observed route and the assumed route with the global nearest-exit assumption. Thus, some guidelines are suggested for the visual accessibility in the design of the complex public underground space.

Generally, the guidelines are to keep the exit or stair in the sight of the people and avoid hiding them behind doorway entrances.

Guideline for Exits: The designer should avoid locating the exit inside a corridor. In most cases of the complex public underground space designs, the designer would like to use a corridor to organize the supporting rooms, such as the toilets, the control room, the facility room, the store, the manager offices, and the exits, out of the sights of the consumers. This is very dangerous as revealed by the model. It is suggested to locate the exit door as obvious to the people in the Exit Access region as possible. If there is other reason to keep it inside a corridor, it is suggested to use a dummy exit door instead of the doorway entrance of the corridor (Fig.5.2-1). The dummy exit door can offer as an

attractive local architectural cue to induce the evacuees to enter. As a result, they will not miss the exit door inside the corridor.

Guideline for Stairs: The designer should avoid locating the stair completely behind a doorway entrance. In most cases of the complex public underground space designs, the designer locates the stair according to the column grid and the room height. If the stair is completely behind a doorway entrance, some evacuee might miss it for its invisibility. Thus, it is suggested to expose at least a part of the stair out of the doorway entrance (Fig.5.2-1). If the exposure of the stair is limited by the column grid or room height, it is suggested to extend several steps of the stair out of the doorway entrance.

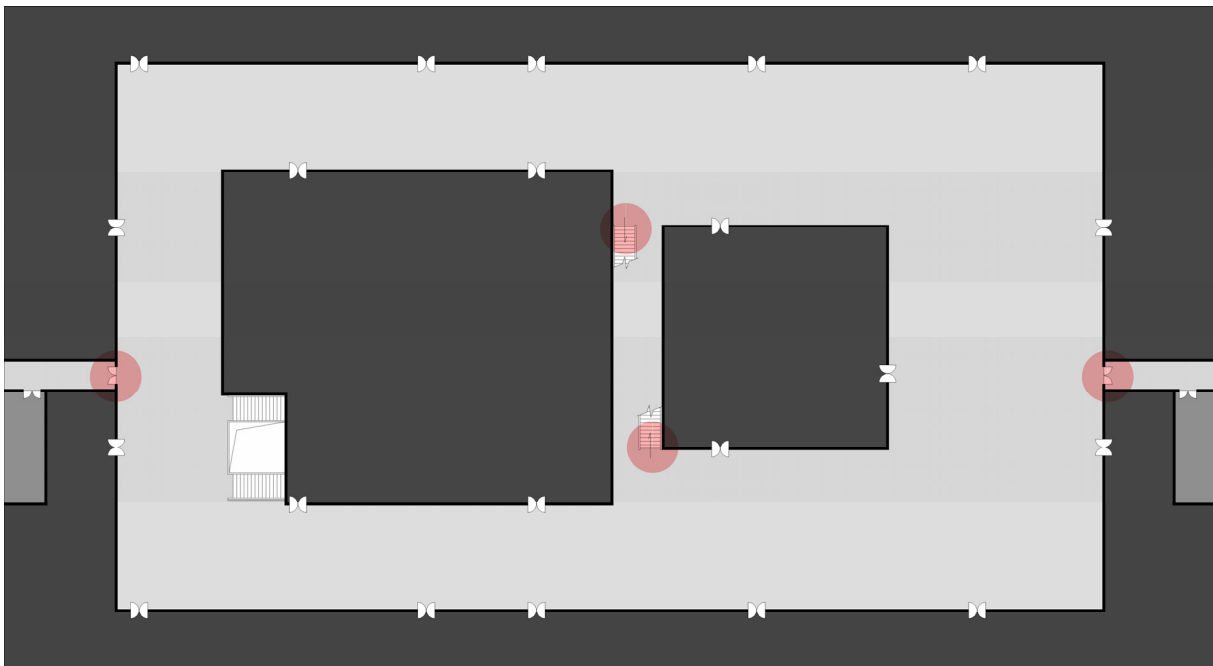


Figure 5.2-1 Modifications on the exits and stairs

5.2.2 Psychological Scale & Physical Scale

As revealed by the computational model, the evacuees will be induced by the doorway entrances when there is no exit or stair in the view. In fact, his choice among the doorway entrances is influenced by their attributes. From the architect's view, the distance depends on the global layout and is not easy to adjust. The two kinds of angular positions depend on the evacuee's dynamic view direction and are not controllable. Thus, the architect can only manipulate the attribute width and height, namely the scale, of the doorway entrance to induce the evacuee. Being able to induce the evacuee, the scale of the doorway entrance has a psychological function.

However, in the current evacuation design process (Tubbs & Meancham, 2007) the architect only manipulates the scale of the doorway entrance according to its physical passing capacity. With the plan of the evacuation flows, the architect calculates the width of every doorway entrance according to the available evacuation time, the average evacuating speed per width unit, and the flow amount passing through this doorway entrance. Thus, the scale of the doorway entrance here is understood and used physically.

Some potential problems will happen when the physical scale mismatches the psychological scale.

On the one hand, when a doorway entrance attracts more evacuees than the planned flow amount because of its clearly attractive psychological scale, this doorway entrance gets overload. The exits and stairs behind it will also get overload. On the other hand, when a doorway entrance attracts fewer evacuees than the planned flow amount because of its vaguely attractive, or even worse a clearly unattractive psychological scale, the other doorway entrances have to experience overloading. Thus, the architect has to ensure the psychological scales of the doorway entrances match the physical scales.

Unfortunately, the psychological scale is not so easy to manipulate as the constant physical scale. As revealed in the computational model, the scale of the doorway entrance has different psychological attractiveness to the evacuee referring to the different scale of the other doorway entrance in the choice set. It means that when one doorway entrance is obviously larger or smaller than the other one, its psychological scale becomes more clearly attractive or unattractive. The evacuees' choices on them will get more chance to have a clear propensity and will be easier to predict. When the difference between the scales of the two doorway entrances is not so obvious, their attractiveness of the psychological scale becomes vague. The evacuees' choices on them will involve more randomness and they will be very unpredictable.

Thus, the guideline for the scales of the doorway entrances is to keep the scales of the doorway entrances on the planned evacuation flow exaggeratedly larger than the others to provide them a clearly attractiveness.

Guideline for Scales of Doorway Entrance: The architect should plan a unique evacuation route for the zone, in which the evacuees can't see the exit or stair directly and have to make choices among the doorway entrances. Along this route there can be two kinds of Doorway Entrances. One is along the route and it is planned to be used by the evacuees. The other is aside the route and it is planned not to be used by the evacuees. The former kind of doorway entrances should be designed with the exaggeratedly larger physical scale than the latter kind of doorway entrances to offer the clearly attractive psychological scales. Meanwhile, they should also have the enough physical scales to hold all the evacuee flow in this zone. In contrast, it will be problematic if the architect plans several routes in such a zone. With the vague psychological scales, the doorway entrances in this zone will get more chances to work differently than the architect's plan.

5.3 Future Direction

As revealed in Chapter 2, local architectural cues exist prevalently in the built environment. After the local architectural cue used in complex public underground space design is investigated in this research, it seems interesting to investigate its utility in other kinds of space designs, such as office building, shopping mall, and etc. It is believed that the existing simulation models can performance better with a sub model supporting the local architectural cues.

To import a sub model for local architectural cues into the existing simulation models, it is necessary to investigate how the local architectural cue works with the other kinds of cues. In other words, the weights of all kinds of the cues should be investigated. Probably, there can be two approaches for all the cues work together. They correspond to the two decision making models: Utility Maximizing Model and Computational Process Model, which are introduced in Chapter 2. One approach is to put all the cues as a set of variables into one function and to assign different weights to them. The weights can be static parameters or dynamically generated according to a distribution. Either the parameter or the distribution should be derived from researches. The other

Architectural Cue Model in Evacuation Simulation for Underground Space Design

approach is to use a set of rules to decide what kind of cue should be used in the route searching process for a specific environment. A systematic research on the cues used in the different kinds of environments should be conducted. Anyway, both approaches provide directions in future research.

Besides this most interesting research direction, to find more indirect evacuation data to validate the proposed model and to apply this model in more real design practices are also future work. Notably, a new PhD research project in Design System group just started to upgrade the artificial vision developed in this thesis, which is expected to provide a better understanding on how the local architectural cues are cognized in built environment.

Manipulation of the local architectural cues is a fundamental skill of the architecture profession. It is interesting and worth continuous investigation.

References

- Allen, G. L. (1999). Spatial Abilities, Cognitive Maps, and Wayfinding: Bases for individual differences in spatial cognition and behavior. In Golledge, R.G. (Eds.), *Wayfinding behavior: cognitive mapping and other spatial processes* (pp. 46-80). Baltimore: The Johns Hopkins University Press.
- Antonini, G., & Bierlaire, M. (2005). A discrete choice framework for acceleration and direction change behaviors in walking pedestrians. In Waldau, N., Gattermann, P., Knoflacher, H., & Schreckenberg, M. (Eds.), *Pedestrian and Evacuation Dynamics 2005* (pp.155-166). Berlin: Springer.
- Arentze, T., & Timmermans, H. J. P. (2000). ALBATROSS: A learning based transportation oriented simulation system: European Institute of Retailing and Services Studies.
- Arentze, T., & Timmermans, H. J. P. (2006). New theory of dynamic activity generation. In *TRB 85th Annual Meeting Compendium of Papers CD-ROM*. Washington DC.
- Arthur, P., & Passini, R. (1990). 1-2-3 Evaluation and Design Guide to Wayfinding. Ottawa: Architectural and Engineering Services.
- Arthur, P., & Passini, R. (1992). *Wayfinding: People, Signs, and Architecture*. New York: McGraw-Hill Book Company.
- Ashihara, Y. (1970). *Exterior Design in Architecture*. New York: Van Nostrand Reinhold Company.
- Augenbroe, G. (2001). Building simulation trends going into the new millennium. In *Proceedings of the seventh international IBPSA conference* (pp.15-27).
- Bailenson, J. N., Blascovich, J., Beall, A. C., & Loomis, J. M. (2001). Equilibrium Theory Revisited: Mutual Gaze and Personal Space in Virtual Environments. *Presence, 10*(6), 583-598.
- Banks, S. B., & Stytz, M. R. (2003). Progress and Prospects for the Development of Computer-Generated Actors for Military Simulation: Part 2 Reasoning System Architectures and Human Behavior Modeling. *Presence, 12*(4), 422-436.
- Baskaya, A., Wilson, C., & Ozcan, Y. Z. (2004). Wayfinding in an unfamiliar environment. *Environment and Behavior, 36*(6), 839-867.
- Bateson, J. E., & Hui, M. K. (1992). The ecological validity of photographic slides and videotapes in simulating the service setting. *Journal of Consumer Research, 19*(2), 271-281.
- Baum, A., & Valins, S. (1977). *Architecture and Social Behavior: Psychological Studies of Social Density*. Hillsdale, New Jersey: Lawrence Erlbaum Associates, Publishers.
- Bell, P. A., Greene, T. C., Fisher, J. D., & Baum, A. (2001). *Environmental Psychology* (5th ed.). Fort Worth: Harcourt College Publishing.
- Blades, M. (1991). Wayfinding theory and research: The need for a new approach. In D. Mark & A. Frank (eds.), *Cognitive and linguistic aspects of geographic space* (pp.137-165). Dordrecht: Kluwer Academic.
- Bovy, P. H. L., & Bradley, M.A. (1985). Route choice analyzed with stated preference approaches. *Transportation Research Record, 1037*, 11-20.
- Bovy, P. H. L., & Stern, E. (1990). *Route Choice: Wayfinding in Transport Networks*. London: Kluwer Academic Publishers.
- Bryan, J. L. (1996). Behavioural response to fire and smoke. In Dilenno et al., (Eds.), *Handbook of Fire Protection Engineering* (pp. 1-241-1-262). Quincy: NFPA.
- Bryan, J. L. (2002). A selected historical review of human behavior in fire. *Fire protection engineering, 16*, 4-10.

Architectural Cue Model in Evacuation Simulation for Underground Space Design

- British Standards Institution (1997). British Standard BS DD240 fire safety engineering in buildings, Part 1: Guide to the application of fire safety engineering principles.
- Burigat, S., & Chittaro, L. (2007). Navigation in 3D virtual environments: Effects of user experience and location-pointing navigation aids. *International Journal of Human-Computer Studies*, 65, 945-958.
- Buxbaum, L. J., Palermo, M. A., Mastrogiovanni, D., Read, M. S., Rosenberg-Pitonyak, E., & Rizzo, A. A., et al. (2007). Assessment of spatial attention and neglect with a virtual wheelchair navigation task. *Journal of Clinical and Experimental Neuropsychology*, 30(6), 650-660.
- Canter, D. (1975). An Introduction to Environmental Psychology. In Canter, D (Eds.), *Environmental interaction: psychological approaches to our physical surroundings* (pp. 1-19). London: Surrey University Press.
- Canter, D., Breaux, J., & Sime, J., (1980). Domestic, Multiple Occupancy and Hospital Fires. In Canter, D. (Eds.), *Fires and Human Behaviour* (pp.117-136). New York: John Wiley & Sons.
- Carmody, J., & Sterling, R. (1983). *Underground Building Design: Commercial and Institutional Structures*. New York: Van Nostrand Reinhold Company.
- Carpman, J., & Grant, M. (2002). Wayfinding: A broad view. In Bechtel, R. & Churchman, A. (Eds.), *Handbook of Environmental Psychology* (pp.427-443). New York: John Wiley and Sons.
- Cheung, C., & Lam, W. (1998). Pedestrian route choices between escalators and stairways in metro stations. *Journal of Transportation Engineering*, 124(3), 277-285.
- Ching, D. K. F. (1996). *Architecture: Form, Space, & Order* (2nd ed.). New York: John Wiley & Sons, Inc.
- Crosby, A. W. (1997). *The measure of reality: Quantification and Western society 1250-1600*. Cambridge: University Press.
- Cubukcu, E., & Nasar, J. L. (2005). Relation of Physical Form to Spatial Knowledge in Largescale Virtual Environments. *Environment and Behavior*, 37, 397-417.
- Cutting, J. E., & Vishton, P. M. (1995). Perceiving layout and knowing distances: the integration, relative potency, and contextual use of different information about depth. In Epstein, W. & Rogers, S. (Eds.), *Perception of space and motion* (Second ed., pp. 69-117). California: Academic Press, Inc.
- Daamen, W., & Hoogendoorn, S. P. (2002). Modeling pedestrians flows through transfer stations. *Transportation Research Board Annual Meeting Pre-print CD-Rom*. Washington: Mira Digital Publishing.
- Dalton, R. C. (2001). The Secret is to Follow Your Nose. In *Proceedings. 3rd International Space Syntax Symposium Atlanta* (pp. 47.1-14).
- de Kort, Y. A. W., Ijsselstein, W. A., Kooijman, J., & Schuurmans, Y. (2003). Virtual laboratories: Comparability of Real and Virtual Environments for Environmental Psychology. *Presence*, 12(4), 360-373.
- Deasy, C., & Lasswell, T. E. (1985). *Designing places for people*. New York: the Whitney Library of Design.
- Dijkstra, J., & Timmermans, H. J. P. (1997). Exploring the possibilities of conjoint measurement as a decision-making tool for virtual wayfinding environments. In: Junge, R. (Eds.), *CAADfutures '97* (pp. 757-770). Munich: Kluwer Academic Publishing.
- Dogu, U., & Erkip, F. (2000). Spatial Factors Affecting Wayfinding and Orientation: A Case Study in a Shopping Mall. *Environment and Behavior*, 32, 731-755.
- Drager, K. H., Lovas, G. G., & Wiklund, J. (1992). EVACSIM, a comprehensive evacuation simulation tool. In J. Sullivan (Eds.), *Proceedings of the 1992 Int. Emergency Management and Engineering Conference, Florida, April 1992* (pp. 101-108). The Society for Computer Simulation (SCS) USA.
- Ellis, S. R., & Menges, B. M. (1997). Judgments of the distance to nearby virtual objects: interaction of viewing conditions and accommodative demand. *Presence: Teleoperators and Virtual Environments*, 6(4), 452-460.

- Evans, G. W. (1982). General Introduction. In Evans, G.W. (Eds.), *Environmental stress* (pp. 1-11). Cambridge: Cambridge University Press.
- Freeman, J., Avons, S. E., Meddis, R., Pearson, D. E., & IJsselsteijn, W. A. (2000). Using behavioral realism to estimate presence: A study of the utility of postural responses to motion stimuli. *Presence: Teleoperators and Virtual Environments*, 9, 149-164.
- Friedman, A. (2005). Frames of reference and direct manipulation based navigation. Delft: Technische Universiteit Delft.
- Galea, E. R. (2001). Simulating Evacuation and Circulation in Planes, Trains, Buildings and Ships Using the EXODUS Software. In Schreckenberg, M., & Sharma, S. (Eds.), *Pedestrian and Evacuation Dynamics 2001* (pp.204-225). Berlin: Springer.
- Garling, T. (1999). Human Information Processing in Sequential Spatial Choice. In Golledge, R.G. (Eds.), *Wayfinding behavior: cognitive mapping and other spatial processes* (pp. 81-98). Baltimore: The Johns Hopkins University Press.
- Garling, T., Book, A., & Lindberg, E. (1986). Spatial orientation and wayfinding in the designed environment: A conceptual analysis and some suggestions for postoccupancy evaluation. *Journal of Architectural Planning Resources*, 3, 55-64.
- Gibson, J. J. (1966). *The senses considered as perceptual systems*. Boston: Houghton Mifflin.
- Gigerenzer, G. (2000). *Adaptive Thinking: rationality in the real world*. Oxford: Oxford University Press.
- Gilinsky, A. S. (1989). The moon illusion in a unified theory of visual space. In M. Hershenson (Eds.), *The moon illusion* (pp.167-192). Hillsdale, NJ: Erlbaum.
- Golledge R G. (1995). Path selection and route preference in human navigation: a progress report, In *Spatial Information Theory Lecture Notes in Computer Science number 988* (pp. 207-222).
- Golledge, R. G. (1999a). Human wayfinding and cognitive maps. In Golledge, R.G. (Eds.), *Wayfinding behavior: cognitive mapping and other spatial processes* (pp. 5-45). Baltimore: The Johns Hopkins University Press.
- Golledge, R. G. (1999b). *Wayfinding behavior: Cognitive mapping and other spatial processes*. Baltimore: Johns Hopkins University Press.
- Graat, E., Midden, C., & Bockholts, P. (1999). Complex evacuation; effects of motivation level and slope of stairs on emergency egress time in a sports stadium. *Safety Science*(31), 127-141.
- Güntürkün, O. (2003). Adult persistence of head-turning asymmetry. *Nature*, 421, 711-712.
- Gwynne, S., Galea, E. R., Owen, M., Lawrence, P., & Filippidis, L. (1999). A review of the methodologies used in evacuation modelling. *Fire and Materials*, 23, 383-388.
- Hair, J. F., Anderson, R. E., Tatham, R. L. & Black, W. C. (1995). *Conjoint analysis*. In *Multivariate data Analysis* (pp. 556-599). Englewood Cliffs NJ: Prentice Hall.
- Halcrow Group Limited. (2002a). PAXPORT. http://www.halcrow.com/pdf/urban_reg/pasport_broch.pdf.
- Halcrow Group Limited. (2002b). PEDROUTE. http://www.halcrow.com/pdf/urban_reg/pedrt_broch.pdf.
- Hall, E. T. (1959). *The Silent Language*. Garden City, New York: Doubleday & Company, Inc.
- Hall, E. T. (1966). *The Hidden Dimension*. Garden City, New York: Doubleday & Company, Inc.
- Hamacher, H.W., & Tjandra, S.A. (2001). Mathematical Modelling of Evacuation Problems: A State of the Art. In Schreckenberg, M., & Sharma, S. (Eds.), *Pedestrian and Evacuation Dynamics 2001* (pp. 59-74). Berlin: Springer.
- Heim, M. (1991). The Metaphysics of Virtual Reality. In Helsel, S.K. & Roth, J.P. (Eds.), *Virtual Reality: Theory, Practice, and Promise* (pp. 27-34). London: Meckler.
- Helbing, D., Farkas, I., & Vicsek, T. (2000). Simulating dynamical features of escape panic. *NATURE*,

Architectural Cue Model in Evacuation Simulation for Underground Space Design

407(28), 487-490.

- Hensen, J. L. M. (2004). Towards more effective use of building performance simulation in design. In Leeuwen, J.P., & Timmermans, H.J.P. (Eds.), *Developments in Design & Decision Support Systems in Architecture and Urban Planning* (pp.291-306). Eindhoven: Technology University of Eindhoven.
- Henson, D. B. (1993). *Visual fields*. Oxford: Oxford University Press.
- Hershberger, R. G. (1974). Predicting the meaning of architecture, in Jon Lang et al. (Eds.), *Designing for Human Behavior: Architecture and the Behavioral Sciences* (pp. 147-156). Stroudsburg: Dowden, Hutchinson and Ross.
- Hershberger, R. G. (1980). A study of meaning and architecture. In Broadbent, G., Bunt, R. & Llorens, T. (Eds.), *Meaning and Behavior in the Built Environment* (pp. 21-42). New York: John Wiley & Sons, Ltd.
- Hershenson, M. (1999). *Visual space perception: A primer*. London: The MIT Press.
- Hillier, B. (1996). *Space is the machine: a configurational theory of architecture*. New York: Cambridge University Press.
- Hochmair, H., & Frank, A. U. (2000). Influence of estimation errors on wayfinding-decisions in unknown street networks – analyzing the least-angle strategy. *Spatial Cognition and Computation*, 2, 283-313.
- Hochmair, H., & Luttich, K. (2006). An Analysis of the Navigation Metaphor And Why It Works for the World Wide Web. *Spatial Cognition and Computation*, 2, 283-313.
- Holl, S., Pallasmaa, J., & Perez-Gomez, A. (1994). *Architecture and Urbanism: Questions of Perception: Phenomenology of Architecture*. Tokyo: a+u Publishing Co., Ltd.
- Holscher, C., Bolhner, S. J., Meilinger, T., & Strubea, G. (2008). Adaptivity of wayfinding strategies in a multi-building ensemble . the effects of spatial structure, task requirements and metric information. *Journal of Environmental Psychology*, Accepted manuscript.
- Holscher, C., Meilinger, T., Vrachliotis, G., Brosamle, M., & Knauff, M. (2006). Up the down staircase: Wayfinding strategies in multi-level buildings. *Journal of Environmental Psychology*, 26, 284-299.
- Hoogendoorn, S. P., & Bovy, P. H. L. (2002). Normative pedestrian behavior theory and modeling. In Taylor, A. P. (Eds.) *Transportation and Traffic Theory in the 21st Century* (pp.219-246). Oxford: Elsevier Science, Ltd.
- Hoogendoorn, S. P., & Bovy, P. H. L. (2004). Pedestrian route-choice and activity scheduling theoryPedestrian route-choice and activity scheduling theory and models. *Transportation Research Part B*(38), 169-190.
- Hoogendoorn, S. P., & Bovy, P. H. L. (2005). Pedestrian Travel Behavior Modeling. *Networks and Spatial Economics*(5), 193-216.
- Hoogendoorn, S. P., & Daamen, W. (2005). Pedestrian Behavior at Bottlenecks. *Transportation Science*, 39(2), 147-159.
- Hopfe, C.J., & Hensen, J. (2006). An approach to use building performance simulation to support design optimization. In *Proceedings Bauinformatik Forum* (pp. 7-CD). Bauhaus Universitat Weimar.
- Hopfe, C.J., Hensen, J., & Plokker, W. (2007). Uncertainty and sensitivity analysis for detailed design support. In *Proceedings of the 10th IBPSA building simulation conference* (pp. 1799-1804).
- Hostikka, S., Korhonen, T., Paloposki, T., Rinne, T., Matikainen, K., & Heliovaara, S. (2007). Development and validation of FDS+Evac for evacuation simulations: Project summary report (Research Notes 2421). Helsinki: Julkaisija Utgivare Publisher.
- Hu, H. H., Gooch, A. A., Thompson, W. B., Smits, B. E., Rieser, J. J., & Shirley, P. (2000). Visual cues for imminent object contact in realistic virtual environments. In *IEEE Visualization Proceedings of the Conference on Visualization* (pp. 179-185).

- IJsselsteijn, W. A., de Ridder, H., Freeman, J., & Avons, S. E. (2000). Presence: Concept, determinants and measurement. In *Proceedings of the SPIE, Human Vision and Electronic Imaging V*, 3959 (pp.520-529).
- IJsselsteijn, W. A., de Ridder, H., Freeman, J., Avons, S. E., & Bouwhuis, D. (2001). Effects of stereoscopic presentation, image motion, and screen size on participative and objective corroborative measures of presence. *Presence: Teleoperators and Virtual Environments*, 10(3), 298-311.
- International Code Council. (2006). International building code. Falls Church, VA: International Codes Council.
- Ittelson, W. H. (1960). Visual Space Perception. New York: Springer Publishing Company, INC.
- Jansen-Osmann, P., & Wiedenbauer, G. (2004). Wayfinding Performance in and the Spatial Knowledge of a Color-coded Building for Adults and Children. *Spatial Cognition & Computation*, 4(4), 337-358.
- Jansen-Osmann, P., Wiedenbauer, G., Schmid, J., & Heil, M. (2007). The Influence of Landmarks and Pre-exposure to a Structural Map During the Process of Spatial Knowledge Acquisition: A Study with Children and Adults in a Virtual Environment. *Spatial Cognition & Computation*, 7(3), 267-285.
- Janzen, G. (2006). Memory for object location and route direction in virtual large-scale space. *The Quarterly Journal of Experimental Psychology*, 59(3), 493-508.
- Janzen, G., Schade, M., Katz, S., & Herrmann, T. (2001). Strategies for detour finding in a virtual maze: The role of the visual perspective. *Journal of Environmental Psychology*, 21, 149-163.
- Johnson, N. R., & Feinberg, W. E. (1997). The impact of exit instructions and number of exits in fire emergencies: A computer simulation investigation. *Journal of Environmental Psychology*(17), 123-133.
- Kobes, M., Helsloot, I., de Vries, B., Oberije, N., & Rosmuller, N. (2007). Fire Response Performance in a Hotel Behavioural Research. In *Conference proceedings Interflam 2007 11th international fire* (Vol. 2, pp. 1429-34).
- Kobes, M., Helsloot, I., de Vries, B., & Post, J. (2008). Safe escape from fire: a question of building techniques or psychonomics? *Tijdschrift voor Veiligheid*, 7(3), 17-33.
- Kretz, T., & Schreckenberg, M. (2006). Floor field and Agent-based Simulation Tool, from <http://arxiv.org/ftp/physics/papers/0609/0609097.pdf>.
- Kuhlen, T., Kraiss, K. F., & Steffan, R. (2000). How VR-based Reach-to-Grasp Experiments Can Help to Understand Movement Organization within the Human Brain. *Presence*, 9(4), 350-359.
- Kuipers, B. (1977). Representing knowledge of large-scale space. Doctoral thesis. MIT Mathematics Department. Cambridge, Mass: MIT Artificial Intelligence Laboratory.
- Kuipers, B. (1978). Modeling Spatial Knowledge. *Cognitive Science: A Multidisciplinary Journal*, 2(2), 129-153.
- Kukla, R., Kerridge, J., Willis, A., & Hine, J. (2001). PEDFLOW: Development of an Autonomous Agent Model of Pedestrian Flow. *Transportation Research Record*, 1774, 11-17.
- Kuligowski, E. D. (2003). The Evaluation of Performance-Based Design Process for a Hotel Building: The Comparison of two Egress Models. Master Thesis. Department of Fire Protection Engineering, University of Maryland, College Park, Maryland.
- Kuligowski, E. D., & Peacock, R. D. (2005). A Review of Building Evacuation Models (Technical Note 1471): Gaithersburg, MD: National Institute of Standards and Technology.
- Lam, W. M. C. (1992). Perception & Lighting as formgivers for architecture. New York: Van Nostrand Reinhold.
- Lang, J. (1987). Creating Architectural Theory. New York: Van Nostrand Reinhold Company Inc.
- Lawson, B. (2001). The Language of SPACE. Oxford: Reed Educational and Professional Publishing Ltd.

Architectural Cue Model in Evacuation Simulation for Underground Space Design

- Le Corbusier. (1986). *Towards a new architecture*. New York: Dover. (Original work published 1931)
- Lombard, M. (1995). Direct responses to people on the screen: Television and personal space. *Communication Research*, 22(3), 288-324.
- Loomis, J. M., Blascovich, J. J., & Beall, A. C. (1999). Immersive virtual environment technology as a basic research tool in psychology. *Behaviour Research Methods, Instruments, & Computers*, 31(4), 557-564.
- Lovas, G. (1994). Modeling and Simulation of Pedestrian Traffic Flow. *Transportation Research Part B*, 429-443.
- Low, David J. (2000). Statistical Physics: Following the Crowd. *Nature*, 407, 465-466.
- Lym, G. R. (1980). *A psychology of building: how we shape and experience our structured spaces*. New Jersey: Prentice-Hall, Inc.
- Lynch, K. (1960). *The Image of The City*. Cambridge: The MIT Press.
- Meilinger, T., Knauff, M., & Bulthoff, H. H. (2008). Working Memory in Wayfinding: A Dual Task Experiment in a Virtual City. *Cognitive Science: A Multidisciplinary Journal*, 32(4), 755-770.
- Ministry of Housing and Urban-Rural Development of the People's Republic of China (MOHURD). (2003). *Codes of the Subway Design (GB50157—2003)*.
- Montello, D. R. (2005). Navigation. In Shah, P. & Miyake, A. (Eds.), *The Cambridge handbook of visuospatial thinking* (pp. 257-94). Cambridge: Cambridge University Press.
- Montello, D. R., & Sas, C. (2006). Human factors of wayfinding in navigation. In Karwowski, W. (Ed.), *International encyclopedia of ergonomics and human factors* (pp. 2003-8). London: CRC Press/Taylor & Francis, Ltd.
- Montgomery, D. C. (1991). *Design and Analysis of Experiments*. Chichester: John Wiley.
- Morganti, F., Carassa, A., & Geminiani, G. (2007). Planning optimal paths: A simple assessment of survey spatial knowledge in virtual environments. *Computers in Human Behavior*, 23, 1982-1996.
- Murakami, Y., Minami, K., Kawasoe, T., & Ishida, T. (2002). Multi-Agent Simulation for Crisis Management. In *IEEE International Workshop on Knowledge Media Networking (KMN-02)* (pp. 135-9).
- Murray, C. D., Bowers, J. M., West, A., Pettifer, S., & Gibson, S. (2000). Navigation, wayfinding, and place experience within a virtual city. *Presence: Teleoperators and Virtual Environments*, 9(5), 435-447.
- Nash, E. B., Edwards, G. W., Thompson, J. A., & Barfield, W. (2000). A review of presence and performance in virtual environments. *International Journal of human-computer Interaction*, 12, 1-41.
- Nassar, K., & Al-Kaisy, A. (2008). Assessing sign occlusion in buildings using discrete event simulation. *Automation in Construction*, 17, 799-808.
- National Fire Protection Association. (2006). *NFPA 101: Life safety code*. Quincy, MA: National Fire Protection Association.
- Newman, E. L., Caplan, J. B., Kirschen, M. P., Korolev, I. O., Sekuler, R., & Kahana, M. J. (2007). Learning your way around town: How virtual taxicab drivers learn to use both layout and landmark information. *Cognition*, 104, 231-253.
- Noman, D. (1988). *The Design of Everyday Things*. New York: Doubleday.
- Norberg-Schulz, C. (1971). *Existence, Space & Architecture*. New York: Praeger Publisher.
- O'Malley, M., & Goldfarb, M. (2002). Comparison of human size identification and discrimination performance in real and simulated environments. In *Proceedings of the IEEE 10th International Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, Haptics 2002* (pp. 10-17).
- O'Neill, M. (1991a). Effects of signage and floor plan configuration on wayfinding accuracy. *Environment and Behavior*, 23, 553-574.

- O'Neill, M. (1991b). Evaluation of a conceptual model of architectural legibility. *Environment and Behavior*, 23, 259-284.
- Omer, I., & Goldblatt, R. (2007). The implications of inter-visibility between landmarks on wayfinding performance: An investigation using a virtual urban environment. *Computers, Environment and Urban Systems*, 31, 520-534.
- Oppewal, H. (1995). Conjoint Experiments and Retail Planning: Modelling Consumer choice of shopping Centre and Reactive Behavior. Doctoral thesis. Eindhoven: Technische Universiteit Eindhoven.
- Oppewal, H., & Timmermans, H. J. P. (1999). Modeling consumer perception of public space in shopping centers. *Environment and behavior*, 31(1), 45-65.
- Orzechowski, M. A. (2004). Measuring Housing Preferences Using Virtual Reality and Bayesian Belief Networks. Eindhoven: Technische Universiteit Eindhoven.
- Ozel, F. (1987). A computer model BGRAF: A cognitive approach to emergency egress simulation. Doctoral thesis, University of Michigan.
- Ozel, F. (1993). How Cognitive Factors Influence Way-Finding. *NFPA Journal*, 87(3), 62-64, 66, 68, 71.
- Pan, X. (2006). Computational Modeling of Human and Social Behaviors For Emergency Egress Analysis. Doctoral thesis, Stanford University.
- Papamichael, K., LaPorta, J., Chauvet, H. (1997). Building design advisor: automated integration of multiple simulation tools. *Automation in construction*, 6 (4), 341-352.
- Passini, R. (1984). Wayfinding in architecture. New York: Van Nostrand Reinhold Company Inc.
- Pazzaglia, F., & Taylor, H. A. (2007). Perspective, Instruction, and Cognitive Style in Spatial Representation of a Virtual Environment. *Spatial Cognition & Computation*, 7(4), 349-364.
- Penn, A., & Turner, A. (2001). Space Syntax Based Agent Simulation. In Schreckenberg, M., & Sharma, S. (Eds.), *Pedestrian and Evacuation Dynamics 2001* (pp.99-114). Berlin: Springer.
- Penn, A., & Turner, A. (2003). Space layout affects search efficiency for agents with vision. In *Proceedings 4th International Space Syntax Symposium* (pp. 9.1-9.16). London: University College London.
- Peponis, J., Dalton, R. C., Wineman, J., & SheepDalton, N. (2003). Path, theme and narrative in open plan exhibition settings. In *Proceedings 4th International Space Syntax Symposium* (pp. 29.1-29.20). London: University College London.
- Peponis, J., & Wineman, J. (2002). Spatial structure of environment and behavior. In Bechtel, R. B. & Churchman, A. (Eds.), *Handbook of environmental psychology* (pp. 271-291). New York: John Wiley.
- Peponis, J., Wineman, J., Rashid, M., Bafna, S., & Kim, S. H. (1998). Describing plan configuration according to the covisibility of surfaces. *Environment and Planning B: Planning and Design*, 25, 693-708.
- Peponis, J., Zimring, C., & Choi, Y. K. (1990). Finding the building in wayfinding. *Environment and Behavior*, 22, 555-590.
- Pertaub, D., Slater, M., & Barker, C. (2002). An Experiment on Public Speaking Anxiety in Response to Three Different Types of Virtual Audience. *Presence*, 11(1), 68-78.
- Porter, T. (1979). How Architects Visualize. London: Studio Vista.
- Rapoport, A. (1982). The Meaning of the Built Environment: A nonverbal communication approach. London: SAGE Publications.
- Raubal, M., & Egenhofer, M. (1998). Comparing the complexity of wayfinding tasks in built environments. *Environment & Planning B*, 25(6), 895-913.
- Raubal, M., & Worboys, M. (1999). A formal model of the process of wayfinding in built environments. In: Freksa, C., & Mark, D. (Eds.), *Spatial Information Theory. Cognitive and Computational Foundations of Geographic Information Science. International Conference, COSIT'99 Lecture Notes in Computer*

Architectural Cue Model in Evacuation Simulation for Underground Space Design

Science Vol. 1661 (pp. 381–399). Berlin: Springer.

- Regan, D. (2000). Human Perception of Objects: early visual processing of spatial form defined by Luminance, Color, Texture, Motion, and Binocular disparity. Sunderland, Massachusetts: Sinauer Associates, Inc.
- Riecke, B. E., Van Veen, H. A. H. C., & Bulthof, H. H. (2002). Visual homing is possible without landmarks: A path integration study in virtual environments. *Presence: Teleoperators and Virtual Environments*, *11*(5), 443-473.
- Rogers, S. (1995). Perceiving Pictorial Space. In Epstein, W. & Rogers, S. (Eds.), *Perception of space and motion* (Second ed., pp.119). California: Academic Press, Inc.
- Rogsch, C., Seyfried, A., & Klingsch, W. (2005). Comparative investigation of the dynamic simulation of foot traffic flow. In Waldau, N., Gattermann, P., Knoflacher, H., & Schreckenberg, M. (Eds.), *Pedestrian and Evacuation Dynamics 2005* (pp.357-362). Berlin: Springer.
- Rose, D., & Foreman, N. (1999). Virtual reality. *The Psychologist*, *12*(11), 550-554.
- Sadeghian, P., Kantardzic, M., Lozitskiy, O., & Sheta, W. (2006). The frequent wayfinding-sequence (FWS) methodology: Finding preferred routes in complex virtual environments. *International Journal of Human-Computer Studies*, *64*, 356-374.
- Santos, G., & Aguirre, B. E. (2004). A critical review of emergency evacuation simulation models. In Peacock, R. D., & Kuligowski, E. D. (Eds.), *Workshop on Building Occupant Movement During Fire Emergencies. Proceedings. Gaithersburg* (pp.27-52). <http://www.fire.nist.gov/bfrlpubs/fire05/PDF/f05012.pdf>
- Savannah Simulations AG. (2006). SimWalk Pedestrian Simulation Software User Guide Version 2.0. http://www.simwalk.com/downloads/SIMWALK_UG_20.zip
- Schadschneider, A. (2001). Cellular Automation Approach to Pedestrian Dynamics - Theory. In Schreckenberg, M., & Sharma, S. (Eds.), *Pedestrian and Evacuation Dynamics 2001* (pp.75-85). Berlin: Springer.
- Scott, D. (1985). Driving simulator to aid road safety. *Automotive engineering*, *93*(11), 79-82.
- Seidel, A. (1982). Way-Finding in Public Spaces: The Dallas Fort Worth, USA Airport. *Environmental Research Association*, *48*, 129-138.
- Shih, N. J., Lin, C. Y., & Yang, C. H. (2000). A virtual-reality-based feasibility study of evacuation time compared to the traditional calculation method. *Fire Safety Journal*, *34*, 377-391.
- Sime, J. (1980). The concept of panic. In Canter, D. (Eds.), *Fires and Human Behavior* (pp. 63-81). Chichester: John Wiley.
- Sime, J. (1985). Movement towards the familiar: Person and place affiliation in a fire entrapment setting. *Environment and Behavior*, *17* (6), 697-724.
- Sime, J. (1987). Research on escape behaviour in fires: New Directions. *Fire Research News* *9*, 3-5.
- Spiers, H. J., & Maguire, E. A. (2008). The dynamic nature of cognition during wayfinding. *Journal of Environmental Psychology*, in press.
- Spring, M. B. (1991). Informating with Virtual Reality. In Helsel, S.K. & Roth, J.P. (Eds.), *Virtual Reality : Theory, Practice, and Promise* (pp. 3-17). London: Meckler.
- Stahl, F. I. (1979). Final Report on the BFIRES/Version 1 Computer simulation of Emergency Egress Behavior During Fires: Calibration and Analysis, NBSIR 79-1713, HEW-NBS Fire and Life Safety Program.
- Stamps, A. E. (1990). Use of photographs to simulate environments: A meta-analysis. *Perceptual and Motor Skills*, *71*, 907-913.
- Stern, E., & Leiser, D. (1988). Levels of spatial knowledge and urban travel modeling. *Geographical*

- Analysis*, 20(2), 140-155.
- Stern, E., Tzelgov, Y., & Henik, A. (1983). Driving efforts and urban route choice. *The Logistics and Transportation Review*, 19(1), 67-79.
- Still, G. K. (2000). Crowd dynamics. Doctoral thesis, Mathematics Department, Warwick University, Coventry, UK.
- Struck, C., Kotek, P., & Hensen, J. (2007). On incorporating uncertainty analysis in abstract building performance simulation tools. In *Proceedings of the 12th symposium for building physics* (pp. 193-205).
- Stytz, M. R., & Banks, S. B. (2003a). Progress and Prospects for the Development of Computer-Generated Actors for Military Simulation, Part 3: The Road Ahead. *Presence*, 12(6), 629-643.
- Stytz, M. R., & Banks, S. B. (2003b). Progress and Prospects for the Development of Computer-Generated Actors for Military Simulation: Part 1: Introduction and Background. *Presence*, 12(3), 312-325.
- Sun, C., & de Vries, B. (2006). An Architecture-Based Model for Underground Space Evacuation. In Borutzky, W., Orsoni, A., & Zobel, R. (Eds.), *Proceedings of the 20-th European Conference on Modelling and Simulation ECMS 2006, Bonn* (pp. 578-583).
- Sun, C., de Vries, B., & Dijkstra, J. (2007). Measuring Human Behaviour Using Head-Cave. In *Computer Aided Architectural Design Futures - Proceedings of the 12th International Conference on Computer Aided Architectural Design Futures* (pp.501-511). Sydney: Springer.
- Sun, C., de Vries, B., Tang, Z. & Dijkstra, J. (2007). A decision making model of the doorway clue for an agent's evacuation simulation. In Zelinka, I., Oplatkova, Z., & Orsoni, A. (Eds.), *Proceedings of the 21-th European Conference on Modelling and Simulation ECMS 2007*. (pp.176-180).
- Sutherland, D. H., Kaufman, K. R., & Moitza, J. R. (1994). Kinematics of normal human walking. In Rose, J., & Gamble, J. G. (Eds.), *HumanWalking* (pp.23-44). Baltimore: Williams and Wilkins.
- Tan, A. A. W. (2003). The Reliability and Validity of Interactive Virtual Reality Computer Experiments. Doctoral thesis, Eindhoven: Technische Universiteit Eindhoven.
- Tan, A. A. W., & de Vries, B. (2000). Using a Virtual Environment for Understanding Real-World Travel Behavior. In *Proceedings of the 5th Conference on Design and Decision Support Systems in Architecture and Urban Planning*. <http://www.ddss.nl/Eindhoven/publications/52>
- Timmermans, H. J. P. (1984). Decompositional multiattribute preference models in spatial choice analysis: a Review of some Recent Developments. *Progress in Human Geography*, 8, 189-221.
- Timmermans, H. J. P., & Golledge, R.C. (1990). Applications of behavior research on spatial problems II: Preference and choice. *Progress in Human Geography*, 14, 311-354.
- Tlauka, M., Brolese, A., Pomeroy, D., & Hobbs, W. (2005). Gender differences in spatial knowledge acquired through simulated exploration of a virtual shopping centre. *Journal of Environmental Psychology*, 25, 111-118.
- TNO (1978). A large-scale simulation system for the study of navigation and driving behavior, Institute for Perception, Documentation sheet 39e, Soesterberg, the Netherlands.
- Tubbs, J. S., & Meancham, B. J. (2007). Egress Design Solutions : A guide to evacuation and crowd management planning. New Jersey: John Wiley & Sons, Inc.
- Turner, A. (2000). Angular Analysis: A Method for the Quantification of Space. Centre for advanced spatial analysis working paper series (23).
- Turner, A., & Penn, A. (2002). Encoding natural movement as an agent-based system: an investigation into human pedestrian behaviour in built environment. *Environment & Planning B*, 29, 473-490.
- Ulrich, R., Simons, R., Losito, B., Fiorito, E., Miles, M., & Zelson, M. (1991). Stress recovery during exposure to natural and urban environments. *Journal of Environmental Psychology*, 11, 201-230.

Architectural Cue Model in Evacuation Simulation for Underground Space Design

- Verlander, N.Q. (1997). Pedestrian Route Choice: An Empirical Study. In *Proceedings of Seminar F of the PTRC European Transport Forum, P415* (pp. 39-49).
- Vriens, M. (1995). Conjoint Analysis in Marketing - Development in stimulus Representation and Segmentation Methods, Doctoral thesis, SOM, RU Groningen.
- Wanger, L. R., Ferwerda, J. A., & Greenberg, D. P. (1992). Perceiving spatial relationships in computer-generated images. *IEEE Computer Graphics & Applications*, 12(3) 44-58.
- Was, J., Gudowski, B., & Matuszyk, P. J. (2006). Social Distances Model of Pedestrian Dynamics. *Lecture notes in computer science*, 4173, 492-501.
- Weisman, J. (1981). Evaluating architectural legibility: Way-finding in the built environment. *Environment and Behavior*, 13, 189-204.
- Werner, S., & Schindler, L. E. (2004). The role of spatial reference frames in architecture. *Environment and Behavior*, 36(4), 461-482.
- Willemsen, P., & Gooch, A. A. (2002). Perceived egocentric distances in real, image-based, and traditional virtual environments. *IEEE Virtual Reality 2002 (VR:02)*, 275-276.
- Wilson, P. N. (1999). Active exploration of a virtual environment does not promote orientation or memory for objects. *Environment and Behavior*, 31(6), 752-763.
- Witmer, B. G., Bailey, J. H., Knerr, B. W., & Parsons, K. C. (1996). Virtual spaces and real world places: Transfer of route knowledge. *International Journal of Human-Computer Studies*, 45, 413-428.
- Witmer, B. G., & Kline, P. B. (1998). Judging perceived and traversed distance in virtual environments. *Presence: Teleoperators and Virtual Environments*, 7(2), 144-167.
- Wittink, D. R., & Cattin, P. (1989). Commercial use of conjoint analysis: An update. *Journal of Marketing*, 53, 91-96.
- Wood, P. G. (1990). A Survey of Behaviour in Fires. In Canter, D. (Eds.), *Fires and Human Behaviour* (pp. 205-234). London: David Fulton Publishers.
- Xia, J., Arrowsmith, C., Jackson, M., & Cartwright, W. (2008). The wayfinding process relationships between decision-making and landmark utility. *Tourism Management*, 29, 445-457.
- Xie, H., Filippidis, L., Galea, E. R., Gwynne, S., BlackShields, D., & Lawrence, P. (2005). Experimental study and theoretical analysis of signage legibility distances as a function of observation angle. In Waldau, N., Gattermann, P., Knoflacher, H., & Schreckenberg, M. (Eds.), *Pedestrian and Evacuation Dynamics 2005* (pp.131-143). Wien, Austria.
- Murakami, Y., Minami, K., Kawasoe, T., & Ishida, T. (2002). Multi-Agent Simulation for Crisis Management. In *IEEE International Workshop on Knowledge Media Networking (KMN-02)* (pp.135-139).
- Zevi, B. (1993). *Architecture as space: How to look at architecture* (Gendel, M. Trans. Revised ed.). New York: Da Capo Press.
- Zimring, C. (1982). The built environment as a source of psychological stress: Impacts of buildings and cities on satisfaction and behavior. In Evans, G. W. (Eds.), *Environmental stress* (pp. 151-78). Cambridge: Cambridge University Press.

Appendixes

Appendix A Architectural Cue Usage in 36 Existing Evacuation Models

According to the details introduced in the literatures about how the evacuee are supposed to search the route to the safety (Ozel, 1987; Drager, Lovas, & Wiklund, 1992; Santos & Aguirre, 2004; Kuligowski & Peacock, 2005; Kretz & Schreckenberg, 2006; Pan, 2006; Savannah Simulations AG, 2006; Hostikka et al., 2007), the methods of the architectural cue modeling in the evacuation simulation models are deduced as the following.

ALLSAFE

The model is developed by InterConsult Group ASA, Norway, in which the evacuee is assumed to escape to the unique exit assigned to him. Thus, the model belongs to the “Designated Route Following” branch in the global category.

ASERI

The model is developed by I.S.T. Integrierte Sicherheits-Technik GmbH, Germany, in which the evacuee can either escape to the global nearest exit with the influence from the other evacuees’ behavior or escape along a path input by the user. Thus, the model belongs to both “Conditional Shortest-Route Following” branch and “Designated Route Following” branch in the global category.

BFIRES-2

The model is developed by F. Stahl, U.S., in which a subroutine called EBIAS minimizes the evacuee’s route to an exit globally with the influence from the familiarity settings on the exits. Thus, the model belongs to “Conditional Shortest-Route Following” branch in the global category.

BGRAF

The model is developed by F. Ozel, University of Michigan, U.S., in which the evacuee does not have the global perspective and has to follow the index called architectural preference level to find the way out. Such levels are subjectively assigned to the architectural cues in the space by the user according to his personal judgment on the attractiveness of the architectural elements. Thus, the model belongs to “Preference Level Following” branch in the local category.

BuildingEXODUS

The model is developed by FSEG Group, University of Greenwich, UK, in which the evacuee will follow the potential map from the place with high value to the place with low value. The value is calculated according to the distance from it to the global nearest exit. The value of the exit itself is zero. If the evacuee is set in the extreme conditions, he can break this rule for a short time. Thus, the model belongs to “Conditional Shortest-Route Following” branch in the global category.

CRISP3

The model is developed by J. Fraser-Mitchell, BRE, UK, in which the evacuees will move to the global nearest exit. However the property of an exit called “door difficulty” can be set by the user or the smoke simulation module. It can replace the original nearest exit with the other. Thus, the model belongs to “Conditional Shortest-Route Following” branch in the global category.

EESCAPE

The model is developed by E. Kendik, Cobau Ltd. Argentinierstr. Austria, in which the evacuee is assumed to escape to the unique exit assigned to him. Thus, the model belongs to the “Designated

Route Following” branch in the global category.

EGRESS

The model is developed by N. Ketchell, AEA Technology, UK, in which the evacuees will move to the global nearest exit. However the potential number assigned to the cell according to the some behavior aspects can influence the choice of the exit. Thus, the model belongs to “Conditional Shortest-Route Following” branch in the global category.

Egress Complexity Model

The model is developed by H.A. Donegan, University of Ulster, UK, in which the evacuee is assumed to escape to the unique exit assigned to him. Thus, the model belongs to the “Designated Route Following” branch in the global category.

EgressPro

The model is developed by P. Simenko, SimCo Consulting, Australia, in which the evacuee is assumed to escape to the unique exit assigned to him. Thus, the model belongs to the “Designated Route Following” branch in the global category.

E-SCAPE

The model is developed by E. Reisser-Weston, Weston Martin Bragg Ltd., UK, in which the evacuee knows all the distances from him to all the exits. A weighting value is assigned to every exit according to the frequency of its usage and the signage about it. The route choice is decided according to the product of the distance and the weight. Thus, the model belongs to “Conditional Shortest-Route Following” branch in the global category.

EVACNET4

The model is developed by Kisko, Francis, and Nobel, University of Florida, U.S., in which the evacuees will be divided into flows to all the exits in a global optimized way to minimize the total evacuation time. Thus, the model belongs to “Designated Flow Field Following” branch in the global category.

EVACSIM¹

The model is developed by K.H. Drager, G.G. Lovas, and J. Wiklund, in which the evacuee can either follow a user specified route or follow the shortest route to the safety according to his perception. Thus, the model belongs to both “Designated Route Following” branch in the global category and “Conditional Nearest-Exit Approaching” branch in the local category.

EvacSim²

The model is developed by L. Poon, at the Victoria University of Technology, Australia, in which the evacuees have the global knowledge of the space and the fire. The route choice is based on not only the shortest distance to the exit but also a set of other factors, such as the “exit familiarity”, “floor layout familiarity”, if the exit is “locked”, if the exit is “blocked by fire”. Thus, the model belongs to “Conditional Shortest-Route Following” branch in the global category.

EXIT89

The model is developed by R.F. Fahy, NFPA, U.S., in which the evacuee can either follow a designated route or search the route by himself. When he searches the route by himself, he will use the global shortest route to the safety if there is no exit blocked manually or by smoke conditions. Otherwise, he will use the shortest route to the safety on the current floor level instead. Thus, the model belongs to both “Designated Route Following” branch and “Conditional Shortest-Route

Following” branch in the global category.

EXITT

The model is developed by B.M. Levin, NBS, U.S., in which the evacuees have the global knowledge of the space and the fire. The route choice is based on a demerit system: traveling one meter gets 1 demerit, leaving from window gets 100 demerits, entering smoke gets 200 demerits. In brief, the decision is made on both the shortest distance and the other conditions. Thus, the model belongs to “Conditional Shortest-Route Following” branch in the global category.

F.A.S.T.

The model is developed by T. Kretz and M. Schreckenber, in which the evacuee is assumed to escape to the unique exit assigned to him. Thus, the model belongs to the “Designated Route Following” branch in the global category.

FDS+Evac

The model is developed by S. Hostikka, T. Korhonen, T. Paloposki, T. Rinne, K. Matikainen and S. Heliövaara in VTT Technical Research Centre of Finland, in which the evacuees implicitly have the global knowledge of the space. They are assumed to follow a “potential flow solution of a two-dimensional incompressible fluid to the given boundary conditions” to an exit. The other influential factors, such as the familiarity of the exit, the visibility of the exit in smoke, and the queuing conditions of the exit, are used to classify all the exits into several preference groups. The evacuees will follow the flow solution to the exit only in the most preferable group. Thus, the model belongs to “Conditional Flow Field Following” branch in the global category.

Fluid Model

The model is developed by Takahashi, Tanaka, and Kose, Ministry of Construction, Japan, in which the evacuees have a global knowledge about the space. They decide the route according to not only the distance to the exit but also the number of evacuees crowding around exits, the rate of egress at the exit. Thus, the model belongs to “Conditional Shortest-Route Following” branch in the global category.

FPEtool

The model is developed by H.E. Nelson, National Bureau of Standards, U.S., in which the evacuees have the global knowledge of the space. They always evacuate to the nearest exit through the most efficient route. Thus, the model belongs to “Designated Route Following” branch in the global category.

GridFlow

The model is developed by D. Purser and M. Bensilum, BRE, UK, in which the evacuees have three strategies to decide their route. The first is to follow a designated route. The second is to move to the global nearest exit according to a distance map with every cell holding the distances from it to every exit. The third is to move to an exit randomly selected. Thus, the model belongs to “Designated Route Following” branch in the global category.

Legion

The model is developed by Legion International, Ltd., UK. A detailed description about how the evacuees choose their route has not been found. However, according to the limited information, the vague descriptions are found that the evacuees will choose the route in an “origin-destination matrix, which simulates the variations in demands over a period of time”. Moreover, choosing a route “by nearest available” is mentioned as one of the evacuee’s schemes. The other influential factors are

also mentioned, such as the population type, the priority, etc. Thus, it is suggested that the model belongs to “Conditional Shortest-Route Following” branch in the global category.

Magnetic Model

The model is developed by S. Okazaki and S. Matsushita, Fukui University, Japan, in which the evacuees have three strategies to decide their route. The first is to follow a designated route. The second is to use the global shortest route to the safety. The third is to move as a magnetized object in a magnetic field. A positive magnetic pole is given to the occupants, obstacles (walls, columns, etc.), and handrails. A negative magnetic pole is located at the goal or exit. Actually, the magnetic field is another kind of flow field. Thus, the model belongs to both “Designated Route Following” branch and “Designated Flow Field Following” branch in the global category.

MASCM

The model is developed by Murakami, in which the evacuees have the global knowledge about the space. They can either use the global shortest route to the safety or use a “familiar route” designated by the user. Furthermore, if there is only one available route to the safety confined by the fire condition, a “leader” will know it and guide the others through this route, although it is neither the shortest the familiar route. Thus, the model belongs to “Designated Route Following” branch, and “Conditional Shortest-Route Following” branch in the global category.

MASSegress

The model is developed by X. Pan, Stanford University, U.S., in which the simulated evacuee has an artificial vision to perceive the local environment. He will use the visually perceived nearest exit around him as the destination and plan the shortest route to it. If there are exits marked as “familiar” by the user in the vision, the normal exit will be ignored. If there is no exit in vision at all, he will explore the space for exit randomly. Thus, the model belongs to both “Conditional Nearest-Exit Approaching” branch and “Random Searching” branch in the local category.

Myriad

The model is developed by G.K. Still, Crowd Dynamics, Ltd, UK. A detailed description about how the evacuees choose their route has not been found. However, according to the limited information, the vague descriptions are found that Myriad measures the distance, width, ease of use, and directional changes from all points within the building space to the exits. Thus, it is suggested that the model can be classified into “Conditional Shortest-Route Following” branch in the global category.

PathFinder

The model is developed by RJA Group, U.S., in which the evacuees have the global knowledge about the space. They use the global shortest route to the exit. Thus, the model belongs to “Designated Route Following” branch in the global category.

PedGo

The model is developed by TraffGo, Ltd., in which the evacuee will follow the route designated by the user. Thus, the model belongs to “Designated Route Following” branch in the global category.

PEDroute

The model is developed by Halcrow Fox Associates, UK, in which the evacuees have the global knowledge about the space. They will decide a route either for the shortest traveling distance or for the balance within all the routes to minimize the total evacuation time. Thus, the model belongs to both “Designated Route Following” branch, and “Designated Flow Field Following” branch in the

global category.

Simulex

The model is developed by P. Thompson, Integrated Environmental Systems, UK, in which the evacuees will use the global optimized route to the exit according to a “Distance Map”. If the optimization is based on the distance, the route to the nearest exit is used. If the other criteria are used to generate a special map, the evacuee can still find the best exit according to this special map. Thus, the model belongs to “Designated Route Following” branch in the global category.

SimWALK

The model is developed by Savannah Simulations AG, in which the evacuees have the global knowledge about the space. Their decision on the route is based on the combination of a social force and a shortest path algorithm. Thus, the model belongs to “Conditional Shortest-Route Following” branch in the global category.

Spatial-Grid Evacuation Model (SGEM)

The model is developed by S.M. Lo, City University in Hong Kong. A detailed description about how the evacuees choose their route has not been found. However, according to the limited information, the vague descriptions are found that the evacuees will decide their route according to not only the minimum distance to the exit region but also the individuals’ familiarity, visual accessibility, directional signs, illumination of the route, etc. As the visual accessibility is mentioned, it is deduced that the simulated evacuee has an artificial vision in some extent, which is probably to support the local information based decision. Thus, it is suggested that the model can be classified into “Conditional Nearest-Exit Approaching” branch in the local category.

STEPS

The model is developed by M. MacDonald, UK, in which the evacuees have the global knowledge about the space in the extent decided by the “awareness” value assigned to the exit. The route choice is based on not only the shortest distance to the exit but also the familiarity with the exit, the number of occupants around the exit, the number of exit lanes. Thus, the model belongs to “Conditional Shortest-Route Following” branch in the global category.

TIMTEX

The model is developed by S.S. Harrington, University of Maryland, U.S., in which the evacuees follow the flow splits designated by the user. Thus, the model belongs to “Designated Flow Field Following” branch in the global category.

VEGAS

The model is developed by G.K. Still, Crowd Dynamics Ltd., UK. A detailed description about how the evacuees choose their route has not been found. However, according to the limited information, the vague descriptions are found that the evacuee decides his route according not only the distances to all the exits but also the other evacuee’s behavior, the distance to the fire/smoke/temperature. Thus, it is suggested that the model can be classified into “Conditional Shortest-Route Following” branch in the global category.

WAYOUT

The model is developed by V.O. Shestopal, Fire Modelling & Computing, Australia, in which the evacuees follow the flow splits designated by the user. Thus, the model belongs to “Designated Flow Field Following” branch in the global category.

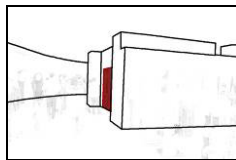
Appendix B Questionnaire on Local Architectural Cues

Questionnaire for local architectural cues in underground evacuation (English Translation)

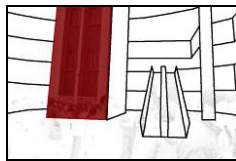
Directions:

Please imagine you are walking in a complex public underground space. Suddenly the broadcast asks you to evacuate immediately. At the same time you can see the elevators and the escalators stop working. In such a circumstance, there are 12 types of architectural elements in your view field, which may offer the hint of the evacuation directions to you. Please use your intuition to sort these elements by your estimation on their probabilities leading to the safety. If you feel an element doesn't offer any hint, please cross it and leave it out of the list. If you have some additional element type offering such a hint, please add it to the list. Any further description on how to use the element or why it has a high or low probability is welcomed.

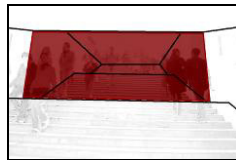
Alternatives:



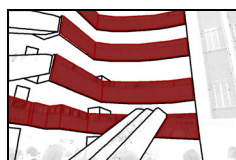
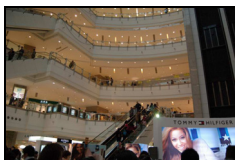
Lift



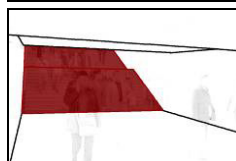
Sight Lift



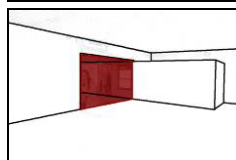
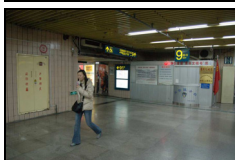
Vertical Outdoor Light



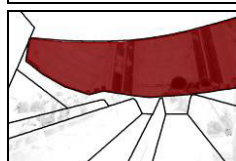
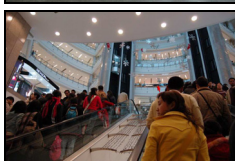
Handrail



Up Stairs

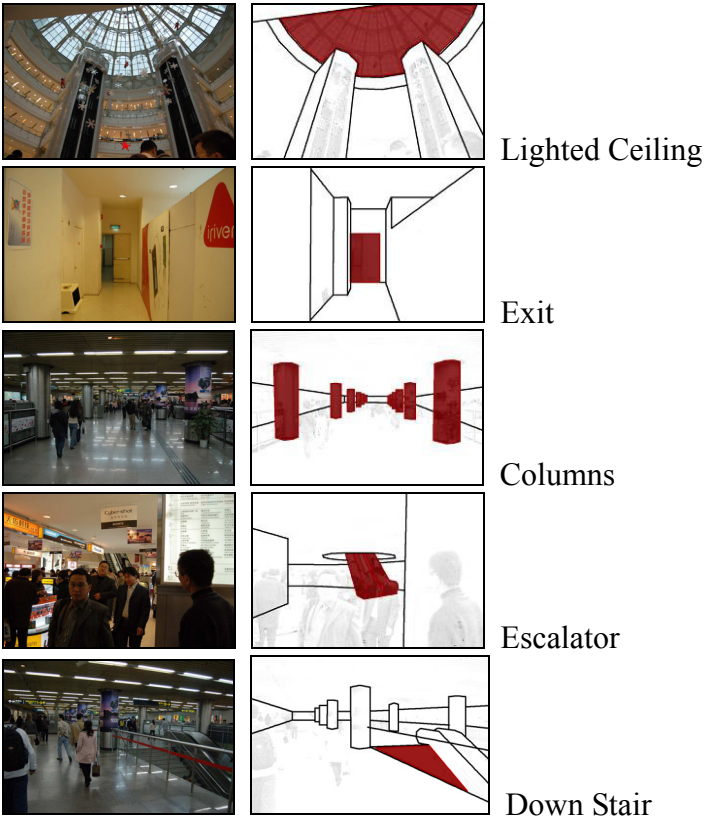


Doorway Entrance



Raised Ceiling

Architectural Cue Model in Evacuation Simulation for Underground Space Design



Highest Probability

Architectural Element

Description



Lowest Probability

| | |
|--|--|
| | |
| | |
| | |
| | |
| | |
| | |
| | |
| | |
| | |
| | |
| | |
| | |
| | |
| | |
| | |
| | |
| | |
| | |
| | |
| | |
| | |

Name:
 Gender:
 Age:
 Phone:
 Email:

Appendix C Design of the CAVE Platform

A special CAVE platform is designed for the virtual evacuation experiments in this research. It includes a semi-hexagonal screen, three projectors fixed in portrait, a height adjuster, an ear phone, and a PC with a three-VGA display adapter (Fig. C-1). The virtual floor in the scenario is designed as high as the physical one, where the participants standing. The participants' eyes are adjusted to 1.75 meter above the floor. With a view field, horizontally 180 degrees and vertically 70 degrees (49 degrees up and 21 degrees down), the participant is able to see the closest object on the floor in front of him in the virtual scenario at the distance of 4547mm (Fig. C-2).

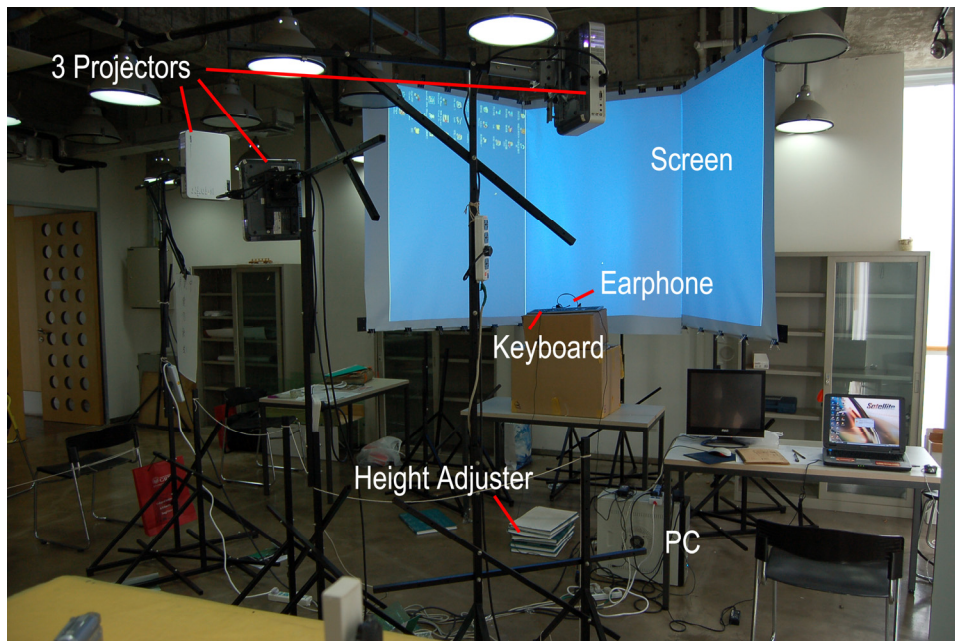


Figure C-1. CAVE platform

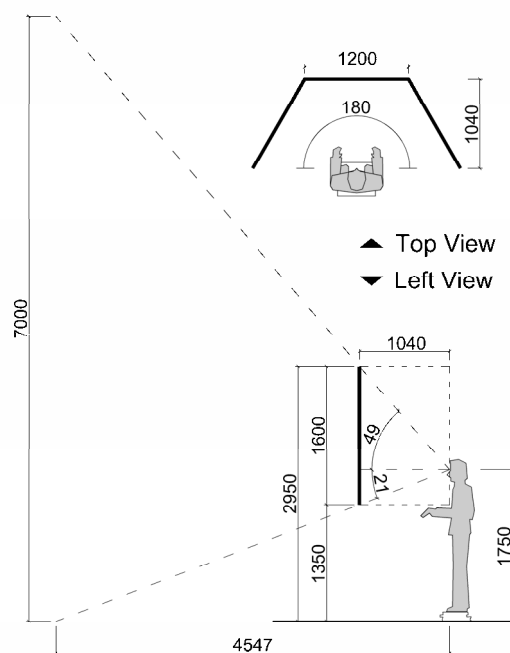


Figure C-2. Dimensions of the CAVE platform

Appendix D Virtual Underground Site in the Observation Experiment

A digital model of the underground space design (Fig. D-1) was built as the virtual environment for the CAVE-based observation. This design is located on west of Huangpu River in Shanghai. It is one of the largest underground developments in the city by 2010, which has 138,129 m² and contains multi-functions as the following:

- West B1 Level: Waiting Room for the coaches (Fig. D-2)
- East B1 Level: Waiting Room for the ships (Fig. D-2)
- West B2 Level: Waiting Room for the coaches (Fig. D-3)
- Middle B2 Level: Shopping (Fig. D-3)
- East B2 Level: Shopping, Car Parking (Fig. D-3)
- West B3 Level: Coach Parking (Fig. D-4)
- Middle & East B3 Level: Car Parking (Fig. D-4)

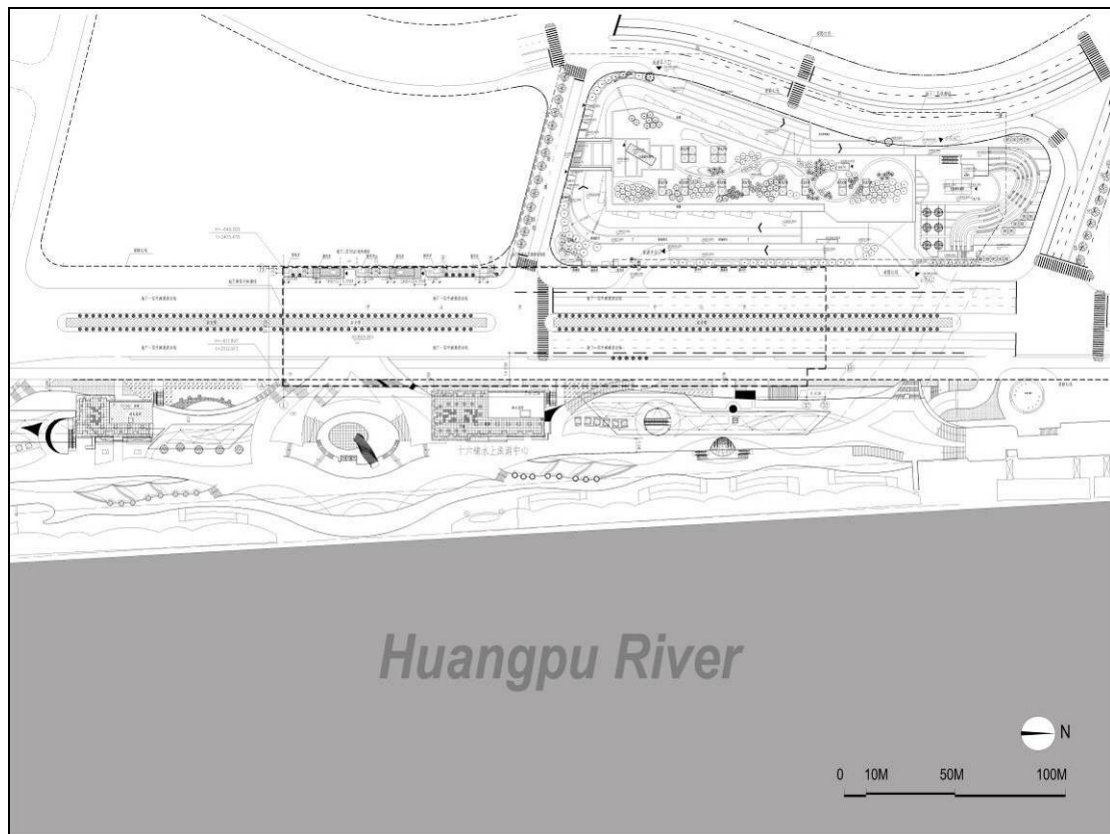


Figure D-1. Master Plan

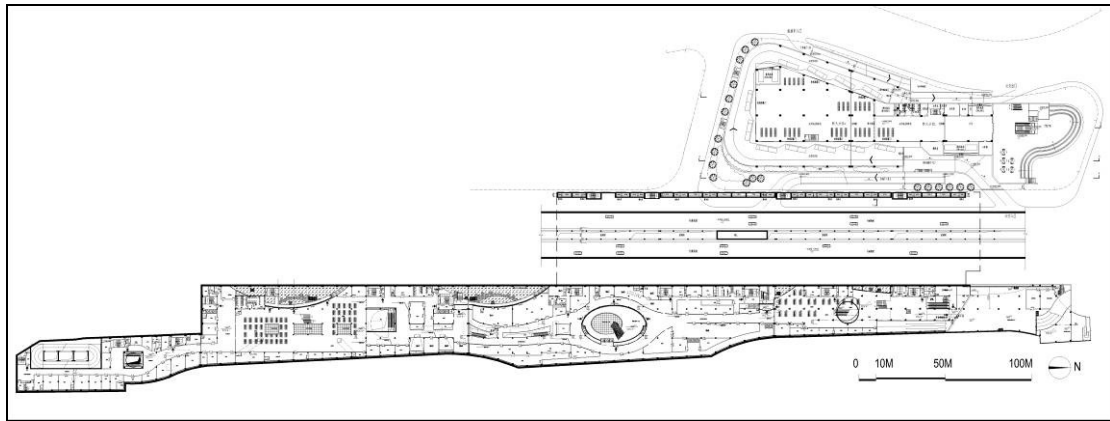


Figure D-2. B1 Plan

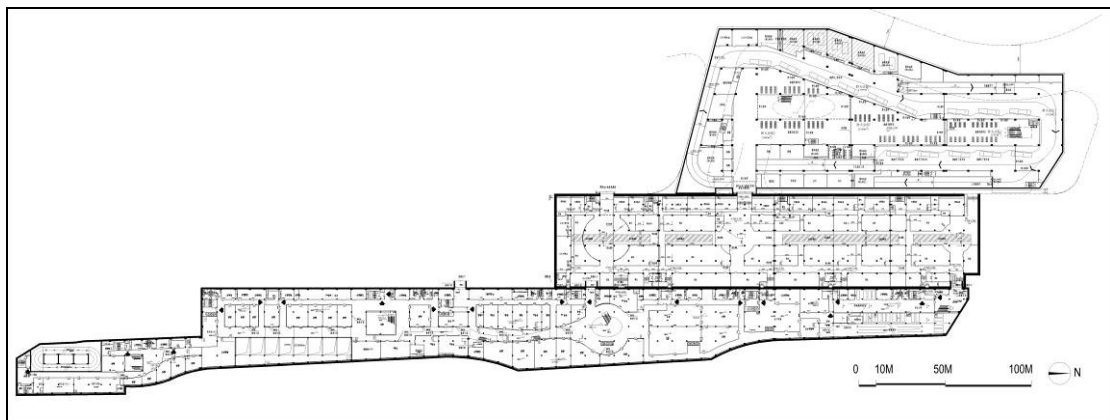


Figure D-3. B2 Plan

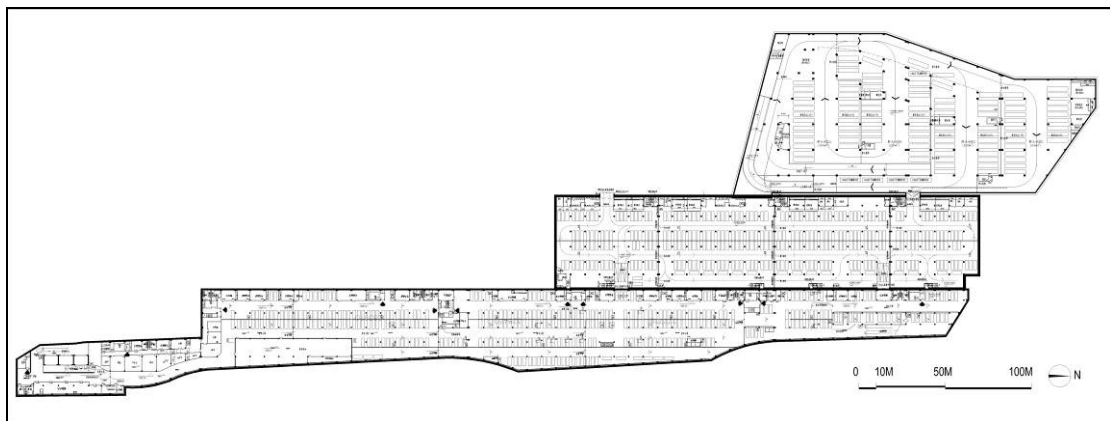


Figure D-4. B3 Plan

Appendix E Document of the Prototype Program

The details in the operation of SpaceSensor are introduced in this appendix. First, the preparation of the space model file in AutoCAD is introduced. Second, the options in the interface of SpaceSensor are introduced. Third, how to make use of the generated files is introduced. Last, the recognition algorithm used in SpaceSensor for the three kinds of local architectural cues is introduced, with which the operator can avoid the errors caused by incorrect modeling and understand the generated files better.

E.1 Preparing Space Model File in AutoCAD

An AutoCAD VBA plug-in program called ExporterForSpaceSensor is developed to extract the space design into a text file, which depicts all the geometric information of the design for the evaluation in SpaceSensor. As a prototype, SpaceSensor still needs the designer to prepare his model in a recognizable way. In fact, all the objects are defined for SpaceSensor according to the layer name and object type in AutoCAD (Table E-1). After the design is prepared according to these transformation rules, ExporterForSpaceSensor can generate a text file. The unit of this file is meter.

Notably, the height of the simulated evacuee's eyes is defined by the distance between the elevation of the line on the Entrance layer and the elevation of the closest floor, which should be set carefully. As concluded in the observation experiment, the visual perception works at a certain height. When an obstacle is higher than the eye height, any cue behind this obstacle can be hidden. Thus, the value of such a height will influence the route searching through the visual perception. For different characteristics of people, it is adjustable in the prototype. However, it has a default value as 1.75 m, which is same as the observation height in the estimation experiment.

Table E-1 Transformation from spatial objects to AutoCAD objects

| Object in the Space | Layer Name | Object Type in AutoCAD | Remarks |
|---------------------------------------|------------|------------------------|-------------------------------------------------------------------------------------------------------------------------------------------|
| Starting point | Entrance | Line | The From Point of the line is the eye position. The To Point of the line points out the head direction. The length of the line is 1. |
| Wall | Wall | 3D Face | All the faces must have two edges perpendicular to each other |
| Floor | Floor | 3D Face | The surface defines the walkable area. |
| Ceiling | Ceiling | 3D Face | |
| Stair | Stair | 3D Face | The faces of the slope are recognized as the walkable stair steps. All the vertical faces must have two edges perpendicular to each other |
| Exit | Exit | 3D Face | The faces must be a little bit (e.g. 0.05 meter) in front of the wall face. |
| Other obstacles for visual perception | Fill | 3D Face | It can block the view to Stair and Exit. |

E.2 Operating the User Interface

Generally, the user interface of SpaceSensor (Fig.E-1) has three zones. The top left zone is the captured artificial vision of the current step. The current step is indicated below the vision. The right zone is the list for all the cues in the cue pool for the current step. The bottom left zone is the control panel. Except the two big buttons (one to start the simulation and the other to stop the simulation) and one indicator to show the name of the current model file, there are several adjustable options. They can be divided into two groups.

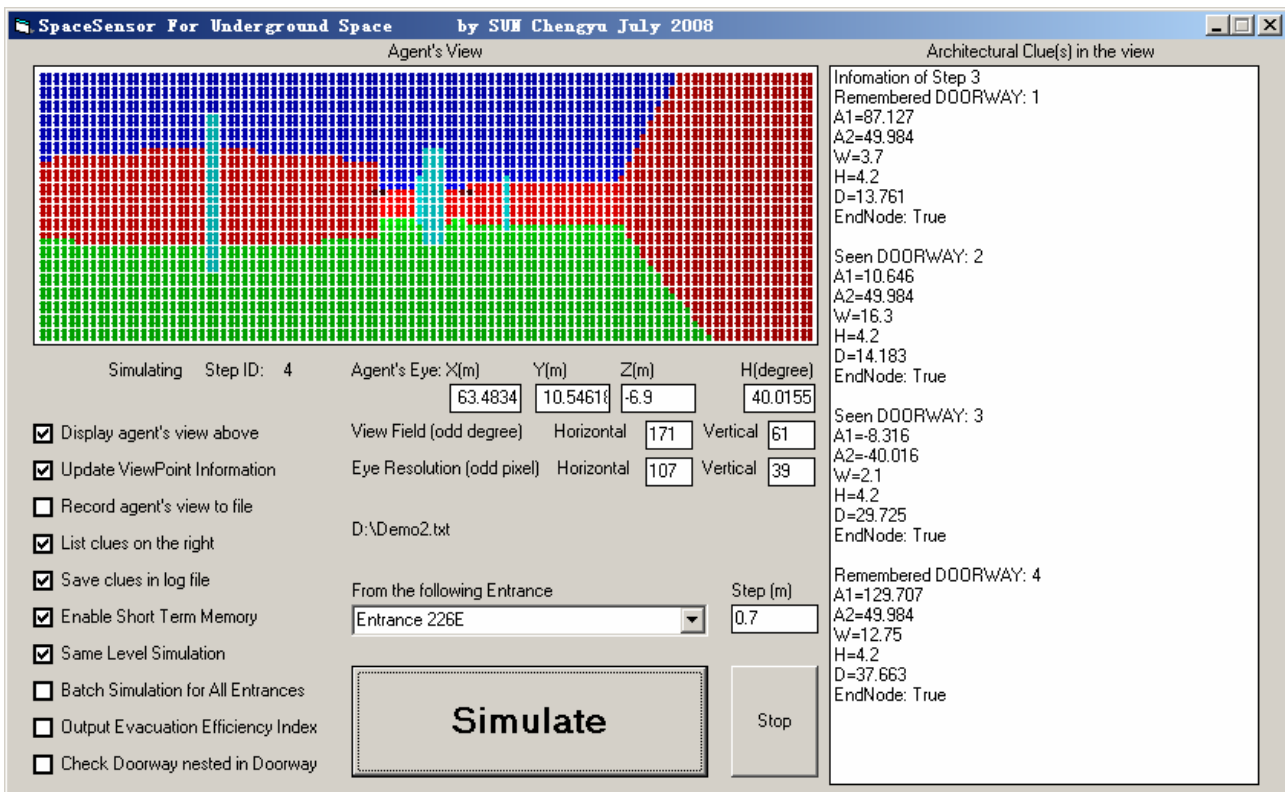


Figure E-1 User Interface of SpaceSensor

First, the right group including all the text boxes defining the properties of the simulated evacuee is introduced. They relate to the current eye position of the simulated evacuee, his view field, the resolution of his vision, the starting point of current simulation, and his step distance.

Eye Position: The four text boxes X, Y, Z, and H in the first line of this group reflect the current coordination of the simulated evacuee's eye. When the simulation is running, these values will be updated dynamically.

View Field: As concluded in the observation experiment, the evacuees' decision depends on the limited view field. Thus, the value of the view field will influence the route searching through the visual perception. In the literature study of Chapter 2, the horizontal monocular view field with two eyes is about 200 degree and the binocular one is about 120 degree. Furthermore, Ozel (1993) concludes that the view field will reduce when the human being gets the emotional arousal under stress. With these considerations, it is adjustable in the prototype. However, it has a default value as 170 degree, which is found as the best value in the pedestrian simulation driven by the artificial vision (Turner & Penn, 2002).

Eye Resolution: With the artificial vision based on a pixel array, the number of the pixels in the

Architectural Cue Model in Evacuation Simulation for Underground Space Design

array, the resolution of the eyes, can influence the route searching through the visual perception. Just as the real people with different eye sights can see things in different distances, the simulated evacuee with a high eye resolution can perceive the local architectural cue far away, while with a low resolution he can only perceive the cues nearby. The resolution is adjustable for the public underground spaces in different scales. However, there is a principle that the resolution should be high enough for the simulated evacuee to see the farthest and smallest cue in the space. Otherwise, the simulated evacuee will miss some cues because of his eye sight. By default, the horizontal resolution is 107 pixels in the prototype, which means that with the default horizontal view field, the simulated evacuee can see a cue 1 meter in width at a distance of 40 meters. All the space designs used in this research are within this limitation.

Entrance List: This list contains one User Defined starting points and all the starting points defined as lines on Entrance layer in AutoCAD. Notably, when User Defined is selected, the eye position input in the Eye Position text boxes will be used as a starting point.

Step: According to the model framework, the evacuation process is implemented in a sequence of steps, which means that the step distance can influence the route searching through the different sets of discrete perceptions along the route. If the step distance is too long, some cues between the two steps can be missed. As concluded by Sutherland, Kaufman, and Moitza (1994), the average step length of mature humans is approximately 0.77 m. A smaller value 0.75m is used in a pedestrian model driven by vision in UK (Turner & Penn, 2002). The value is adjustable in SpaceSensor. However, a default value of 0.7 m is used according to the smaller body size of Chinese people.

Next, the left group including all the switches controlling how SpaceSensor behaves is introduced. Some of them control the display on the user interface during the simulation. Some of them control the output files. And the rest provides the extra control on the simulation process.

Display agent's view above: It controls whether the artificial vision is displayed in the top left zone. To speed up the simulation, it can be switched off.

Update ViewPoint Information: It controls whether the current eye position is updated in Eye Position text boxes on the right dynamically. To speed up the simulation, it can be switched off.

Record agent's view to file: It controls whether the artificial vision displayed in the top left zone is recorded in a sequence of BMP files. If it is switched on, please be sure the option Display agent's view above is also switched on.

List clues on the right: It controls whether the cues in the current decision making process is displayed in the right zone. To speed up the simulation, it can be switched off.

Save cues in log file: It controls whether the whole decision making process is recorded in a log file. It is recommended to keep it on. With the log file, the architect can make a detailed analysis on the design problem.

Enable Short-term Memory: It controls whether the simulated evacuee can remember cues, which he saw before and can't see in the current position. It is recommended to keep it on. It is only used for some special applications.

Same Level Simulation: It controls whether the simulation will terminate when the simulated evacuee can leave the current floor. When it is on, the simulation will terminate if the evacuee

arrives at any Up Stair or Exit on the current floor. When it is off, the simulation will terminate if the evacuee arrives at the ground floor or an Exit. The former is a part of the latter simulation. Sometimes this switch can save a lot of time when the operator only wants to know the route on the current floor.

Batch Simulation for All Entrances: It controls whether all the entrances listed in Entrance List except the User Defined one are simulated one by one automatically. When it is off, only the selected entrance will be simulated.

Output Evacuation Efficiency Index: It controls whether SpaceSensor will output a file containing LEEI.

Check Doorway nested in Doorway: It controls whether the simulated evacuee will regard a doorway with some other doorway nested in it as an available cue. In most cases of the complex public underground space designs, it should be off. Only in the case that the space is so narrow that the evacuee can perceive almost all the space behind the Doorway Entrance when he can see some other Doorway Entrance nested in this one, this switch should be set on.

Briefly, the operator can leave all these options with the default values. In most cases, it can work well with the complex public underground space designs.

E.3 Reading the Output Files

After the simulation, SpaceSensor generates several files. They can be useful for the detailed analysis on the space design. If the file name of the model file is called “X.txt”, all the output files are defined as in Table E-2.

Table E-2 Output files of SpaceSensor

| File Name | Content |
|---------------------|--------------------------------------------------------------------------------------------|
| X_Doorway.txt | All the perceived Doorway Entrances are recorded here. |
| X_Efficiency.txt | All the LEEI values are recorded here. |
| X_Entrances.txt | All the defined entrances in AutoCAD are recorded here. |
| X_Exit.txt | All Exits with properties in the model file no matter perceived or not are recorded here. |
| X_Floor.txt | The edges of the floor surfaces are recorded here. |
| X_Log.txt | The whole decision making process in every step with every cue is recorded here. |
| X_ShortestPath.txt | The shortest path from the starting point to the safety is recorded here. |
| X_SimulatedPath.txt | The simulated path with all the steps is recorded here. |
| X_Stair.txt | All Stairs with properties in the model file no matter perceived or not are recorded here. |
| X_StairKeys.txt | The detailed Stair information is recorded here. |

In all these files, the most important two are the log file and the simulated path file. Another AutoCAD VBA plug-in called ImporterForSpaceSensor is developed to draw the simulated path on the original design, which can indicate the route visually. Meanwhile, if there is some problem in the route, the operator can check the log file to see what the simulated evacuee “thinks” in details, which contributes to the analysis very much.

E.4 Understanding the Image-Based-Recognition Algorithms

The artificial vision is based on a basic 3D rendering method, which results in a pixel array with an extended data structure. As shown in Fig.3.4-2 an environment model in 3D faces will be rendered into a pixel array as in Fig.3.4-3 with the extended data relating to each pixel. They are: Pixel Type, Face Index, and Intersection Coordination of the Pixel. Generally, each pixel relates to a face.

Pixel Type indicates the type of the related surface, such as Wall, Ceiling, Floor, Exit, Stair, and Filling Face. In the CAD model, surface types are defined through layer names (Table E-1).

Face Index indicates the index of the related face in the 3D faces of the space model, which enables the agent to find out the geometric information of a specific face.

Intersection Coordinates of the Pixel indicates the exact intersection coordination of the related face and a ray from the eye to the pixel center.

With the artificial vision based on the pixel array and the space model as the agent's environmental knowledge, the simulated evacuee can implement the recognition on the architectural cues of the Exit, Up Stair and Doorway Entrance. In the following the algorithms are introduced one by one.

E.4.1 Recognition of Exit

The recognition process of exit consists of two phases.

In the first phase, when the space model is read for the first time, SpaceSensor initialize the groups of the exit faces. The faces on Exit layer with any shared edge will be grouped as one exit. In each group, there must be two 3D Faces to form a rectangular exit door. With the geometric information of these two faces, SpaceSensor calculates the attributes: Height, Width, Key Point and Target Point for this exit (Fig.E-2). Furthermore, two rays along the two opposite directions perpendicular to the 3D faces of this exit are cast. The direction of the ray touching a Wall face with the minimum distance is the Escape Direction. Thus, the operator must ensure the 3D Faces of the exits are a little bit in front of the Wall faces.

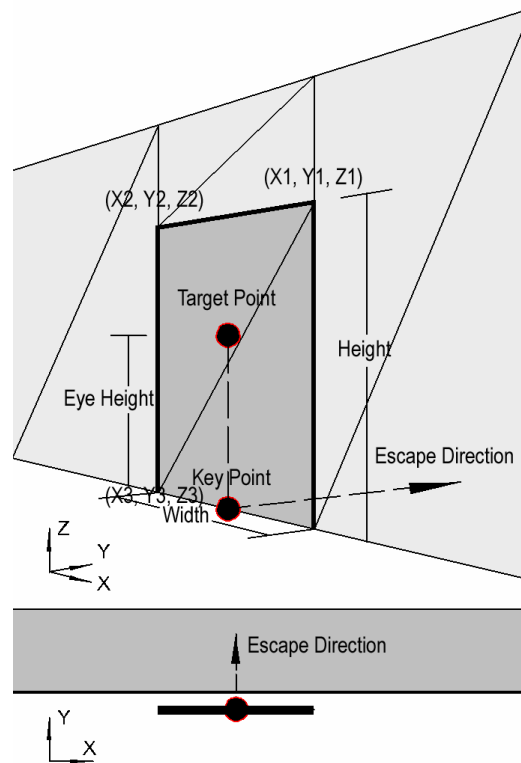


Figure E-2. Recognition of Exit

In the second phase, when the simulated evacuee perceives the architectural cue through his vision in every step, any pixel with the Pixel Type “Exit” will be found out from the pixel array. SpaceSensor searches all the Face Indexes in the initialized exit face groups for an exit including the same Face Index as the Face Index of the exit pixel. With an initialized exit linked to an exit pixel in the vision, this exit is regarded as perceived. According to the initialized attribute Target Point and the current eye position, the attributes Distance and A1 are calculated. According to the initialized attribute Egress Direction and the view direction of the current eye position, the attribute A2 is calculated.

E.4.2 Recognition of Stair

The recognition process of stairs also consists of two phases.

In the first phase, when the space model is read for the first time, SpaceSensor initialize the groups of the stair faces. The faces on Stair layer with any shared edge will be grouped as one stair. In each group, there must be two kinds of 3D Faces. One is the walkable face and the other is the side face. If the three nodes of a face sharing two different Z coordination values and their projections on the XY plane are nonlinear, the face is a walkable face. With the walkable faces found, the rest is the side face.

For every walkable face, SpaceSensor calculates the five attributes: Key Point, Escape Direction, Height, Width, and Average Z (Fig.E-3). The Keypoint is calculated as the midpoint of the two nodes of a walkable face with the same Z value. The Escape Direction points out to which direction the evacuee will go upstairs on the walkable face. It is oriented perpendicular to the edge holding the Key Point and pointed from the nodes with the lower Z value to the nodes with higher Z value. The Height is the vertical distance between the three nodes. The Width is the distance between the

two nodes with the same Z value. The Average Z is calculated from the Z coordination values of the three nodes.

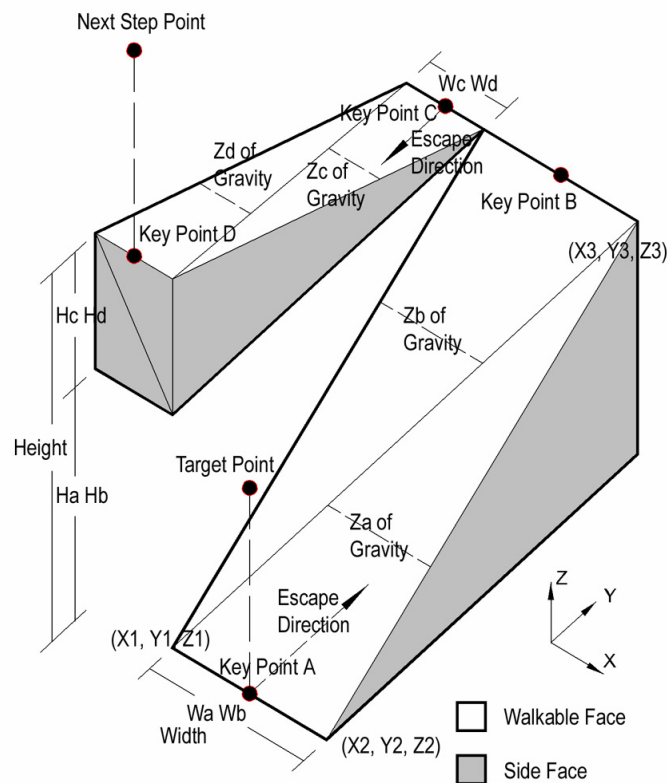


Figure E-3. Recognition of Stair

In the second phase, when the simulated evacuee perceives the architectural cue through his vision in every step, any pixel with the Pixel Type “Stair” will be found out in the pixel array. SpaceSensor searches all the Face Indexes in the initialized stair face groups for a stair including the same Face Index as the Face Index of the stair pixel. With an initialized stair group linked to a stair pixel in the vision, this stair is regarded as perceived. If all the Average Z values of this stair are lower than the Z coordination of the current standing point, the stair is rejected as a stair going down. If it is not rejected, it is treated as an Up Stair cue perceived. According to the initialized attributes and the current eye position, the attributes Distance, Width, Height, A1, and A2 are calculated. SpaceSensor first finds out the Key Point (Key Point A) with the same Z value as the current stand point. The point above this Key Point for one body height is defined as Target Point, where the evacuee will move toward if he selects this stair. The highest Key Point (Key Point D) in all the Key Points in this stair is regarded as the Next Step Point, where evacuee will be located after going upstairs. The Escape Direction related to this highest Key Point will be the head direction of the simulated evacuee after he goes upstairs. The distance between the Target Point and the Next Step Point is the value of the attribute H. The Width of the walkable face holding the Key Point related to the Target Point is regarded as the attribute Width of the stair. According to the Target Point and the current eye position, the attributes Distance and A1 are calculated. According to the Egress Direction of the walkable face related to the Target Point and the view direction of the current eye position, the attribute A2 is calculated.

E.4.3 Recognition of Doorway Entrance

The recognition process of Doorway Entrance consists of three phases with two branches in the second phase.

In the first phase, SpaceSensor searches for specific pixel pairs leading to Doorway Entrances. The simulated evacuee scans the pixel array for all the pixel pairs with two “Wall” pixels. In the artificial vision, the both outer columns of the Pixel Array are excluded demarcating the boundaries for the scan process. Generally, there are five types of Wall-Wall pixel pairs identifiable during the scan process (Fig.E-4). As indicated by the Face Index, every pixel links to a 3D face. These pairs distinguish to each other for the different connection types between the two linked faces. If the two faces are different from each other and don’t have any shared node, the linked pixel pair is regarded as the useful pixel pair (e.g. Pixel Pair I), which is always on the corner of the Doorway Entrance. To avoid repeated recognition of the same doorway corner, the algorithm skips all the Wall-Wall pixel pairs (e.g. Pixel Pair V) under the Pixel Pair I. Other Wall-Wall pixel pairs with the two linked faces sharing the same Face Index (e.g. Pixel Pair II), or one node (e.g. Pixel Pair IV), or two nodes (e.g. Pixel Pair III) are ignored.

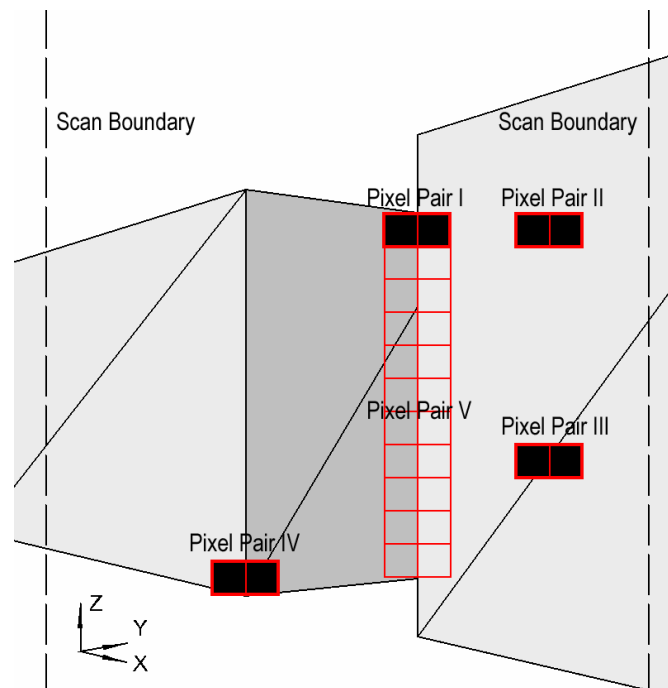


Figure E-4. Recognition of pixel pairs for Doorway Entrances

In the second phase, two types of doorways entrances are discriminated. First, SpaceSensor calculates the distances from the two pixels to the eye according to the related Intersection Coordinates of the Pixel. Next, comparing the Face Index of the relative nearer pixel with the Face Index of the pixel outside the scan boundary on the same row, the simulated evacuee can tell whether the face related to the nearer pixel extends out of the scan boundary. If the above two Face Indexes are different, which means the face related to the nearer pixel does not extend out of the scan boundary, the simulated evacuee executes the strategy type A, otherwise, type B.

In the both types, the agent compares the two angles projected on the XY plane between the eye and two specific points to calculate the Survey Direction. The difference between the two strategy types is the method on how to find the two specific points. The angle calculation is based on the

Architectural Cue Model in Evacuation Simulation for Underground Space Design

counter-clockwise angular coordination, which means that the direction of the view is zero in angle. Turning left gets positive angle, and turning right gets negative one.

In Strategy Type A: The simulated evacuee uses the two nodes of the face related to the nearer pixel on the XY plane as the two specific points for the Survey Direction calculation. If the nearer pixel is on the right of the pixel pair, the Survey Direction is from the node with the smaller angle to the node with the bigger angle. If the nearer pixel is on the left, the Survey Direction is from the node with the bigger angle to the node with the smaller angle (Fig.E-5).

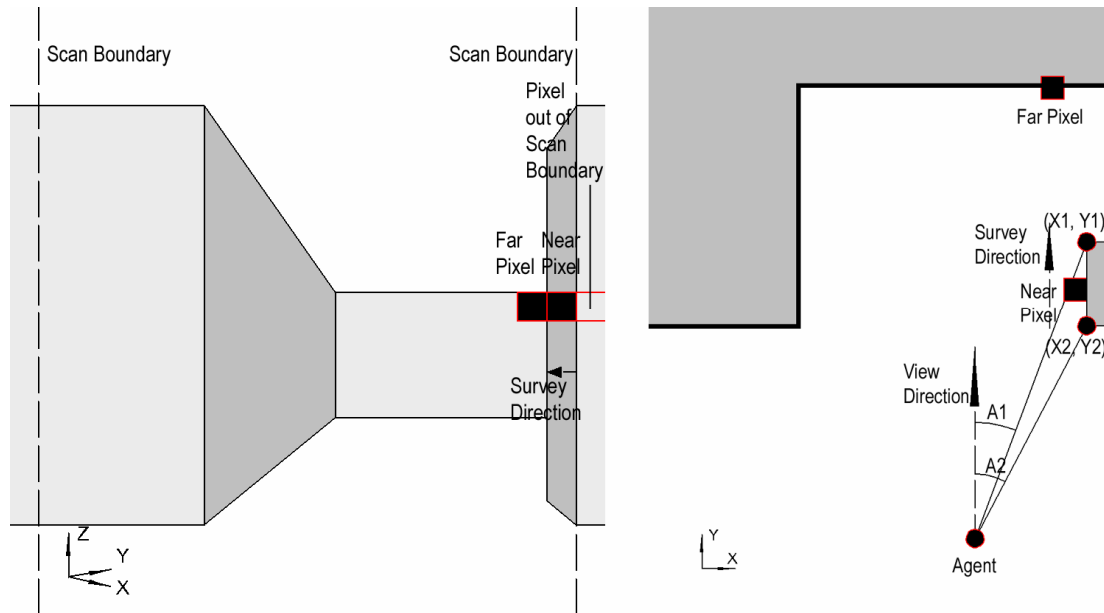


Figure E-5. Strategy type A in Doorway Entrance recognition

In Type B: The simulated evacuee uses the two projected intersections on the XY plane as the two specific points for the Survey Direction calculation. One is the intersection related to the nearer pixel in the pair, which is called Near Pixel. The other is the intersection of the pixel in the outer column with the same Face Index and on the same row as Near Pixel, which is called Side Pixel. With these two pixels, the Survey Direction is always from the projected intersection of Side Pixel to the projected intersection of Near Pixel (Fig.E-6).

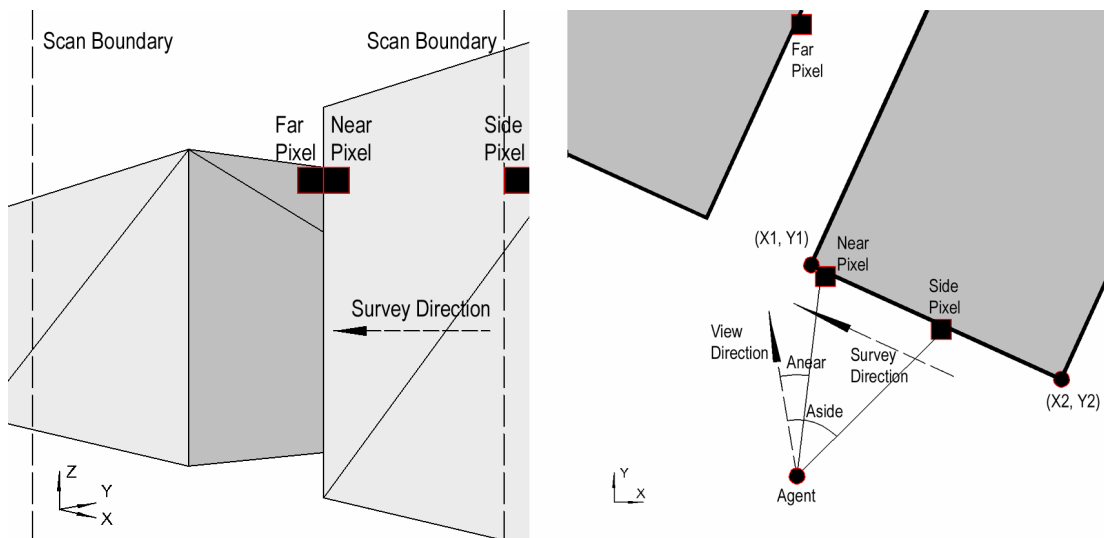


Figure E-6. Strategy type B in Doorway Entrance recognition

In the last phase, the attributes of the Doorway Entrance is calculated (Fig.E-7). On the XY Plane the node of the wall face relating to the nearer pixel pointed by the Survey Direction is regarded as ID Point A. Next, SpaceSensor casts a ray along the Survey Direction from ID Point A to find the other corner of the doorway entrance as ID Point B. Adding a body height to the mid point between the two ID Points results in the Target Point. The distance between the two ID Points is the Width of the doorway entrance. SpaceSensor casts another ray from the ground to the ceiling on ID Point A to get the Height of the doorway entrance. SpaceSensor searches all the wall faces for a face sharing ID Point A and not sharing the same plane with the wall face linked by the nearer pixel. On the XY plane such a face will determine the Escape Direction from the ID Point A to its other node. According to the Escape Direction and the view direction SpaceSensor calculates A2. The Distance and A1 value are calculated according to the eye position and the Target Point.

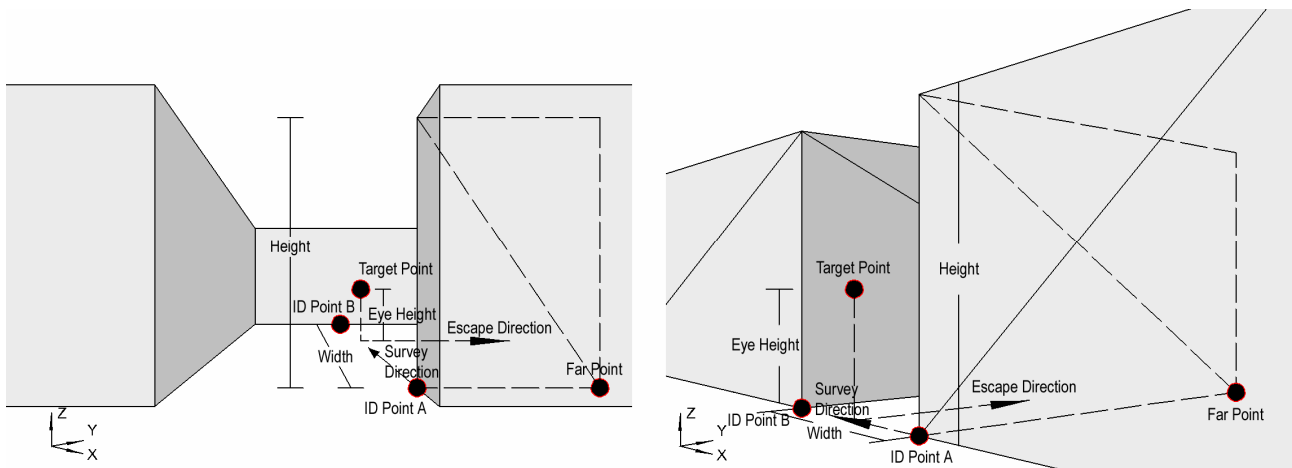


Figure E-7. Extracted attributes in Doorway Entrance recognition

Appendix F Statistic Reports

In this appendix, there is a set of statistic reports containing four regression reports of the four cue pair types. The estimated function used here is the hypothetic function (Eq.2).

F.1 Report of the Cue Pair D-D

| Model Fitting Information | | | | |
|---------------------------|------------------------|------------------------|----|------|
| Model | Model Fitting Criteria | Likelihood Ratio Tests | | |
| | -2 Log Likelihood | Chi-Square | df | Sig. |
| Intercept Only | 938.867 | | | |
| Final | 261.825 | 677.042 | 28 | .000 |

| Goodness-of-Fit | | | |
|-----------------|------------|----|------|
| | Chi-Square | df | Sig. |
| Pearson | 19.301 | 21 | .566 |
| Deviance | 19.269 | 21 | .568 |

| Pseudo R-Square | |
|-----------------|------|
| Cox and Snell | .132 |
| Nagelkerke | .176 |
| McFadden | .102 |

| Likelihood Ratio Tests | | | | |
|------------------------|------------------------------------|------------------------|----|------|
| Effect | Model Fitting Criteria | Likelihood Ratio Tests | | |
| | -2 Log Likelihood of Reduced Model | Chi-Square | df | Sig. |
| Intercept | 261.825(a) | .000 | 0 | . |
| A1 | 422.955 | 161.131 | 6 | .000 |
| A2 | 277.177 | 15.353 | 6 | .018 |
| D | 526.627 | 264.802 | 6 | .000 |
| W | 530.956 | 269.132 | 6 | .000 |
| H | 272.706 | 10.881 | 4 | .028 |

The chi-square statistic is the difference in -2 log-likelihoods between the final model and a reduced model. The reduced model is formed by omitting an effect from the final model. The null hypothesis is that all parameters of that effect are 0.

a This reduced model is equivalent to the final model because omitting the effect does not increase the degrees of freedom.

| | | Parameter Estimates | | | | | | | 95% Confidence Interval for Exp(B) | |
|-----------|-----------|---------------------|------------|---------|------|------|--------|-------------|------------------------------------|--|
| Picked(a) | | B | Std. Error | Wald | df | Sig. | Exp(B) | Lower Bound | Upper Bound | |
| Picked | Intercept | .003 | .171 | .000 | 1 | .988 | | | | |
| | [A1=1] | .770 | .116 | 44.208 | 1 | .000 | 2.160 | 1.721 | 2.710 | |
| | [A1=2] | .935 | .122 | 59.206 | 1 | .000 | 2.548 | 2.008 | 3.233 | |
| | [A1=3] | .668 | .118 | 32.128 | 1 | .000 | 1.950 | 1.548 | 2.456 | |
| | [A1=4] | .357 | .116 | 9.548 | 1 | .002 | 1.430 | 1.140 | 1.793 | |
| | [A1=5] | .044 | .120 | .137 | 1 | .712 | 1.045 | .827 | 1.321 | |
| | [A1=6] | -.177 | .115 | 2.352 | 1 | .125 | .838 | .668 | 1.050 | |
| | [A1=7] | 0(b) | . | . | 0 | . | . | . | . | |
| | [A2=1] | -.280 | .117 | 5.708 | 1 | .017 | .756 | .600 | .951 | |
| | [A2=2] | -.383 | .123 | 9.686 | 1 | .002 | .682 | .536 | .868 | |
| | [A2=3] | -.194 | .120 | 2.612 | 1 | .106 | .824 | .651 | 1.042 | |
| | [A2=4] | -.214 | .121 | 3.135 | 1 | .077 | .808 | .638 | 1.023 | |
| | [A2=5] | -.180 | .120 | 2.238 | 1 | .135 | .836 | .660 | 1.057 | |
| | [A2=6] | -.030 | .118 | .065 | 1 | .799 | .971 | .771 | 1.222 | |
| | [A2=7] | 0(b) | . | . | 0 | . | . | . | . | |
| | [D=1] | 1.217 | .120 | 102.013 | 1 | .000 | 3.376 | 2.666 | 4.275 | |
| | [D=2] | 1.033 | .116 | 79.481 | 1 | .000 | 2.808 | 2.238 | 3.524 | |
| | [D=3] | 1.150 | .120 | 92.488 | 1 | .000 | 3.157 | 2.497 | 3.990 | |
| | [D=4] | .382 | .117 | 10.719 | 1 | .001 | 1.466 | 1.166 | 1.843 | |
| | [D=5] | .304 | .119 | 6.491 | 1 | .011 | 1.356 | 1.073 | 1.714 | |
| | [D=6] | -.068 | .120 | .315 | 1 | .575 | .935 | .738 | 1.184 | |
| | [D=7] | 0(b) | . | . | 0 | . | . | . | . | |
| | [W=1] | -1.449 | .121 | 144.186 | 1 | .000 | .235 | .185 | .298 | |
| | [W=2] | -1.125 | .119 | 89.676 | 1 | .000 | .325 | .257 | .410 | |
| | [W=3] | -.897 | .118 | 58.049 | 1 | .000 | .408 | .324 | .514 | |
| | [W=4] | -.842 | .119 | 50.267 | 1 | .000 | .431 | .341 | .544 | |
| | [W=5] | -.296 | .118 | 6.300 | 1 | .012 | .744 | .590 | .937 | |
| | [W=6] | -.081 | .120 | .459 | 1 | .498 | .922 | .729 | 1.166 | |
| | [W=7] | 0(b) | . | . | 0 | . | . | . | . | |
| | [H=1] | -.192 | .100 | 3.700 | 1 | .054 | .825 | .678 | 1.004 | |
| | [H=2] | -.333 | .102 | 10.597 | 1 | .001 | .717 | .587 | .876 | |
| [H=3] | -.226 | .123 | 3.401 | 1 | .065 | .797 | .627 | 1.014 | | |
| [H=4] | -.239 | .123 | 3.766 | 1 | .052 | .788 | .619 | 1.002 | | |
| [H=5] | 0(b) | . | . | 0 | . | . | . | . | | |

a The reference category is: Unpicked.

b This parameter is set to zero because it is redundant.

| Classification | | | |
|--------------------|-----------|--------|-----------------|
| Observed | Predicted | | |
| | Unpicked | Picked | Percent Correct |
| Unpicked | 1921 | 625 | 75.5% |
| Picked | 1050 | 1199 | 53.3% |
| Overall Percentage | 62.0% | 38.0% | 65.1% |

F.2 Report of the Cue Pair S-S

| Model Fitting Information | | | | |
|---------------------------|------------------------|------------------------|----|------|
| Model | Model Fitting Criteria | Likelihood Ratio Tests | | |
| | -2 Log Likelihood | Chi-Square | df | Sig. |
| Intercept Only | 1630.367 | | | |
| Final | 300.631 | 1329.736 | 28 | .000 |

| Goodness-of-Fit | | | |
|-----------------|------------|----|------|
| | Chi-Square | df | Sig. |
| Pearson | 74.460 | 20 | .000 |
| Deviance | 73.551 | 20 | .000 |

| Pseudo R-Square | |
|-----------------|------|
| Cox and Snell | .246 |
| Nagelkerke | .329 |
| McFadden | .205 |

| Likelihood Ratio Tests | | | | |
|------------------------|------------------------------------|------------------------|----|------|
| Effect | Model Fitting Criteria | Likelihood Ratio Tests | | |
| | -2 Log Likelihood of Reduced Model | Chi-Square | df | Sig. |
| Intercept | 300.631(a) | .000 | 0 | . |
| A1 | 392.713 | 92.082 | 6 | .000 |
| A2 | 457.277 | 156.646 | 6 | .000 |
| D | 1085.445 | 784.814 | 6 | .000 |
| W | 438.408 | 137.776 | 6 | .000 |
| H | 525.614 | 224.983 | 4 | .000 |

The chi-square statistic is the difference in -2 log-likelihoods between the final model and a reduced model. The reduced model is formed by omitting an effect from the final model. The null hypothesis is that all parameters of that effect are 0.

a This reduced model is equivalent to the final model because omitting the effect does not increase the degrees of freedom.

| | | Parameter Estimates | | | | | | | 95% Confidence Interval for Exp(B) | |
|-----------|------------------|---------------------|------------|---------|------|-------|--------|-------------|------------------------------------|--|
| Picked(a) | | B | Std. Error | Wald | df | Sig. | Exp(B) | Lower Bound | Upper Bound | |
| Picked | Intercept | -1.033 | .190 | 29.492 | 1 | .000 | | | | |
| | [A1=1] | .459 | .125 | 13.384 | 1 | .000 | 1.583 | 1.238 | 2.024 | |
| | [A1=2] | .854 | .132 | 41.846 | 1 | .000 | 2.348 | 1.813 | 3.041 | |
| | [A1=3] | .272 | .132 | 4.227 | 1 | .040 | 1.313 | 1.013 | 1.701 | |
| | [A1=4] | .184 | .127 | 2.104 | 1 | .147 | 1.202 | .937 | 1.542 | |
| | [A1=5] | -.202 | .124 | 2.675 | 1 | .102 | .817 | .641 | 1.041 | |
| | [A1=6] | -.110 | .121 | .835 | 1 | .361 | .896 | .707 | 1.134 | |
| | [A1=7] | 0(b) | . | . | 0 | . | . | . | . | |
| | [A2=1] | .850 | .132 | 41.687 | 1 | .000 | 2.339 | 1.807 | 3.027 | |
| | [A2=2] | .334 | .143 | 5.470 | 1 | .019 | 1.396 | 1.056 | 1.847 | |
| | [A2=3] | 1.132 | .135 | 69.915 | 1 | .000 | 3.101 | 2.378 | 4.043 | |
| | [A2=4] | .362 | .135 | 7.197 | 1 | .007 | 1.436 | 1.102 | 1.870 | |
| | [A2=5] | .075 | .137 | .305 | 1 | .581 | 1.078 | .825 | 1.410 | |
| | [A2=6] | -.090 | .139 | .417 | 1 | .518 | .914 | .696 | 1.201 | |
| | [A2=7] | 0(b) | . | . | 0 | . | . | . | . | |
| | [D=1] | 2.473 | .139 | 317.714 | 1 | .000 | 11.854 | 9.032 | 15.558 | |
| | [D=2] | 2.433 | .138 | 309.210 | 1 | .000 | 11.398 | 8.691 | 14.950 | |
| | [D=3] | 2.232 | .141 | 251.061 | 1 | .000 | 9.315 | 7.068 | 12.276 | |
| | [D=4] | 1.329 | .134 | 98.057 | 1 | .000 | 3.779 | 2.904 | 4.916 | |
| | [D=5] | .915 | .144 | 40.528 | 1 | .000 | 2.496 | 1.883 | 3.307 | |
| | [D=6] | .365 | .142 | 6.597 | 1 | .010 | 1.441 | 1.090 | 1.904 | |
| | [D=7] | 0(b) | . | . | 0 | . | . | . | . | |
| | [W=1] | -1.043 | .124 | 71.252 | 1 | .000 | .352 | .276 | .449 | |
| | [W=2] | -.932 | .131 | 50.326 | 1 | .000 | .394 | .304 | .509 | |
| | [W=3] | -.585 | .126 | 21.699 | 1 | .000 | .557 | .435 | .712 | |
| | [W=4] | -.612 | .120 | 25.964 | 1 | .000 | .542 | .429 | .686 | |
| | [W=5] | -.083 | .123 | .456 | 1 | .500 | .920 | .722 | 1.172 | |
| | [W=6] | -.012 | .128 | .009 | 1 | .925 | .988 | .769 | 1.270 | |
| | [W=7] | 0(b) | . | . | 0 | . | . | . | . | |
| | [H=1] | -1.053 | .106 | 97.813 | 1 | .000 | .349 | .283 | .430 | |
| | [H=2] | -1.160 | .107 | 116.510 | 1 | .000 | .314 | .254 | .387 | |
| | [H=3] | -.555 | .136 | 16.589 | 1 | .000 | .574 | .440 | .750 | |
| [H=4] | .074 | .128 | .333 | 1 | .564 | 1.077 | .838 | 1.383 | | |
| [H=5] | 0(b) | . | . | 0 | . | . | . | . | | |

a The reference category is: Unpicked.

b This parameter is set to zero because it is redundant.

| Classification | | | |
|--------------------|-----------|--------|-----------------|
| Observed | Predicted | | |
| | Unpicked | Picked | Percent Correct |
| Unpicked | 1809 | 737 | 71.1% |
| Picked | 591 | 1567 | 72.6% |
| Overall Percentage | 51.0% | 49.0% | 71.8% |

F.3 Report of the Cue Pair E-E

| Model Fitting Information | | | | |
|---------------------------|------------------------|------------------------|----|------|
| Model | Model Fitting Criteria | Likelihood Ratio Tests | | |
| | -2 Log Likelihood | Chi-Square | df | Sig. |
| Intercept Only | 1570.559 | | | |
| Final | 244.449 | 1326.110 | 28 | .000 |

| Goodness-of-Fit | | | |
|-----------------|------------|----|------|
| | Chi-Square | df | Sig. |
| Pearson | 19.537 | 20 | .487 |
| Deviance | 19.557 | 20 | .486 |

| Pseudo R-Square | |
|-----------------|------|
| Cox and Snell | .257 |
| Nagelkerke | .344 |
| McFadden | .216 |

| Likelihood Ratio Tests | | | | |
|------------------------|------------------------------------|------------------------|----|------|
| Effect | Model Fitting Criteria | Likelihood Ratio Tests | | |
| | -2 Log Likelihood of Reduced Model | Chi-Square | df | Sig. |
| Intercept | 244.449(a) | .000 | 0 | . |
| A1 | 336.237 | 91.787 | 6 | .000 |
| A2 | 265.821 | 21.372 | 6 | .002 |
| D | 1122.959 | 878.510 | 6 | .000 |
| W | 567.717 | 323.268 | 6 | .000 |
| H | 292.691 | 48.241 | 4 | .000 |

The chi-square statistic is the difference in -2 log-likelihoods between the final model and a reduced model. The reduced model is formed by omitting an effect from the final model. The null hypothesis is that all parameters of that effect are 0.

a This reduced model is equivalent to the final model because omitting the effect does not increase the degrees of freedom.

| | | Parameter Estimates | | | | | | | 95% Confidence Interval for Exp(B) | |
|-----------|-----------|---------------------|------------|---------|------|------|--------|-------------|------------------------------------|--|
| Picked(a) | | B | Std. Error | Wald | df | Sig. | Exp(B) | Lower Bound | Upper Bound | |
| Picked | Intercept | -.255 | .193 | 1.753 | 1 | .186 | | | | |
| | [A1=1] | .661 | .128 | 26.870 | 1 | .000 | 1.938 | 1.509 | 2.488 | |
| | [A1=2] | .726 | .136 | 28.585 | 1 | .000 | 2.068 | 1.584 | 2.698 | |
| | [A1=3] | .495 | .133 | 13.792 | 1 | .000 | 1.640 | 1.263 | 2.130 | |
| | [A1=4] | .327 | .129 | 6.395 | 1 | .011 | 1.387 | 1.076 | 1.787 | |
| | [A1=5] | .262 | .135 | 3.760 | 1 | .052 | 1.299 | .997 | 1.693 | |
| | [A1=6] | -.307 | .134 | 5.299 | 1 | .021 | .735 | .566 | .955 | |
| | [A1=7] | 0(b) | . | . | 0 | . | . | . | . | |
| | [A2=1] | .166 | .135 | 1.509 | 1 | .219 | 1.181 | .906 | 1.540 | |
| | [A2=2] | -.269 | .149 | 3.276 | 1 | .070 | .764 | .571 | 1.023 | |
| | [A2=3] | .092 | .137 | .447 | 1 | .504 | 1.096 | .837 | 1.435 | |
| | [A2=4] | -.188 | .146 | 1.659 | 1 | .198 | .829 | .623 | 1.103 | |
| | [A2=5] | .092 | .143 | .412 | 1 | .521 | 1.096 | .828 | 1.450 | |
| | [A2=6] | -.228 | .144 | 2.503 | 1 | .114 | .796 | .600 | 1.056 | |
| | [A2=7] | 0(b) | . | . | 0 | . | . | . | . | |
| | [D=1] | 2.539 | .141 | 323.848 | 1 | .000 | 12.671 | 9.610 | 16.708 | |
| | [D=2] | 2.331 | .135 | 296.651 | 1 | .000 | 10.293 | 7.894 | 13.421 | |
| | [D=3] | 1.798 | .139 | 168.282 | 1 | .000 | 6.039 | 4.602 | 7.924 | |
| | [D=4] | 1.120 | .131 | 72.586 | 1 | .000 | 3.063 | 2.368 | 3.963 | |
| | [D=5] | .373 | .142 | 6.920 | 1 | .009 | 1.452 | 1.100 | 1.916 | |
| | [D=6] | -.087 | .145 | .355 | 1 | .551 | .917 | .690 | 1.219 | |
| | [D=7] | 0(b) | . | . | 0 | . | . | . | . | |
| | [W=1] | -1.909 | .142 | 179.665 | 1 | .000 | .148 | .112 | .196 | |
| | [W=2] | -1.471 | .135 | 118.245 | 1 | .000 | .230 | .176 | .299 | |
| | [W=3] | -1.188 | .131 | 81.731 | 1 | .000 | .305 | .236 | .394 | |
| | [W=4] | -1.055 | .133 | 62.558 | 1 | .000 | .348 | .268 | .452 | |
| | [W=5] | -.567 | .130 | 19.049 | 1 | .000 | .567 | .440 | .732 | |
| | [W=6] | -.186 | .130 | 2.029 | 1 | .154 | .831 | .643 | 1.072 | |
| | [W=7] | 0(b) | . | . | 0 | . | . | . | . | |
| | [H=1] | -.663 | .112 | 35.043 | 1 | .000 | .516 | .414 | .642 | |
| | [H=2] | -.623 | .113 | 30.252 | 1 | .000 | .536 | .430 | .670 | |
| | [H=3] | -.597 | .142 | 17.765 | 1 | .000 | .550 | .417 | .726 | |
| [H=4] | -.219 | .137 | 2.567 | 1 | .109 | .803 | .615 | 1.050 | | |
| [H=5] | 0(b) | . | . | 0 | . | . | . | . | | |

a The reference category is: Unpicked.

b This parameter is set to zero because it is redundant.

| Classification | | | |
|--------------------|-----------|--------|-----------------|
| Observed | Predicted | | |
| | Unpicked | Picked | Percent Correct |
| Unpicked | 1849 | 572 | 76.4% |
| Picked | 608 | 1430 | 70.2% |
| Overall Percentage | 55.1% | 44.9% | 73.5% |

F.4 Report of the Cue Pair S-E

| Model Fitting Information | | | | |
|---------------------------|------------------------|------------------------|----|------|
| Model | Model Fitting Criteria | Likelihood Ratio Tests | | |
| | -2 Log Likelihood | Chi-Square | df | Sig. |
| Intercept Only | 1960.894 | | | |
| Final | 456.186 | 1504.707 | 29 | .000 |

| Goodness-of-Fit | | | |
|-----------------|------------|----|------|
| | Chi-Square | df | Sig. |
| Pearson | 74.911 | 51 | .016 |
| Deviance | 74.378 | 51 | .018 |

| Pseudo R-Square | |
|-----------------|------|
| Cox and Snell | .185 |
| Nagelkerke | .247 |
| McFadden | .148 |

| Likelihood Ratio Tests | | | | |
|------------------------|------------------------------------|------------------------|----|------|
| Effect | Model Fitting Criteria | Likelihood Ratio Tests | | |
| | -2 Log Likelihood of Reduced Model | Chi-Square | df | Sig. |
| Intercept | 456.186(a) | .000 | 0 | . |
| W | 849.863 | 393.676 | 13 | .000 |
| A1 | 514.167 | 57.981 | 6 | .000 |
| D | 1033.330 | 577.144 | 6 | .000 |
| H | 466.198 | 10.012 | 4 | .040 |

The chi-square statistic is the difference in -2 log-likelihoods between the final model and a reduced model. The reduced model is formed by omitting an effect from the final model. The null hypothesis is that all parameters of that effect are 0.

a This reduced model is equivalent to the final model because omitting the effect does not increase the degrees of freedom.

| Parameter Estimates | | | | | | | | | |
|---------------------|------------------|--------|------------|---------|------|------|--------|------------------------------------|-------------|
| Picked(a) | | B | Std. Error | Wald | df | Sig. | Exp(B) | 95% Confidence Interval for Exp(B) | |
| | | | | | | | | Lower Bound | Upper Bound |
| Picked | Intercept | -1.334 | .139 | 92.744 | 1 | .000 | | | |
| | [W=1.0] | .268 | .120 | 5.006 | 1 | .025 | 1.307 | 1.034 | 1.652 |
| | [W=2.0] | .258 | .119 | 4.701 | 1 | .030 | 1.294 | 1.025 | 1.635 |
| | [W=3.0] | .439 | .134 | 10.684 | 1 | .001 | 1.552 | 1.192 | 2.019 |
| | [W=4.0] | .792 | .144 | 30.068 | 1 | .000 | 2.208 | 1.664 | 2.931 |
| | [W=5.0] | .821 | .136 | 36.404 | 1 | .000 | 2.273 | 1.741 | 2.969 |
| | [W=6.0] | 1.178 | .143 | 68.264 | 1 | .000 | 3.248 | 2.456 | 4.295 |
| | [W=7.0] | 1.088 | .156 | 48.916 | 1 | .000 | 2.968 | 2.188 | 4.026 |
| | [W=8.0] | -1.086 | .172 | 39.622 | 1 | .000 | .338 | .241 | .474 |
| | [W=9.0] | -.606 | .197 | 9.475 | 1 | .002 | .546 | .371 | .802 |
| | [W=10.0] | -.544 | .197 | 7.667 | 1 | .006 | .580 | .395 | .853 |
| | [W=11.0] | -.459 | .170 | 7.291 | 1 | .007 | .632 | .453 | .882 |
| | [W=12.0] | -.109 | .172 | .400 | 1 | .527 | .897 | .640 | 1.257 |
| | [W=13.0] | .311 | .137 | 5.113 | 1 | .024 | 1.364 | 1.042 | 1.785 |
| | [W=14.0] | 0(b) | . | . | 0 | . | . | . | . |
| | [A1=1.00] | .484 | .096 | 25.232 | 1 | .000 | 1.622 | 1.343 | 1.958 |
| | [A1=2.00] | .603 | .095 | 40.074 | 1 | .000 | 1.828 | 1.516 | 2.203 |
| | [A1=3.00] | .624 | .115 | 29.384 | 1 | .000 | 1.866 | 1.489 | 2.337 |
| | [A1=4.00] | .412 | .110 | 14.115 | 1 | .000 | 1.510 | 1.218 | 1.873 |
| | [A1=5.00] | .312 | .108 | 8.302 | 1 | .004 | 1.366 | 1.105 | 1.689 |
| | [A1=6.00] | .186 | .099 | 3.528 | 1 | .060 | 1.204 | .992 | 1.461 |
| | [A1=7.00] | 0(b) | . | . | 0 | . | . | . | . |
| | [D=1.00] | 1.840 | .097 | 359.319 | 1 | .000 | 6.298 | 5.207 | 7.618 |
| | [D=2.00] | 1.650 | .100 | 274.171 | 1 | .000 | 5.204 | 4.281 | 6.327 |
| | [D=3.00] | 1.448 | .117 | 151.896 | 1 | .000 | 4.253 | 3.379 | 5.354 |
| | [D=4.00] | .876 | .113 | 60.042 | 1 | .000 | 2.402 | 1.924 | 2.998 |
| | [D=5.00] | .654 | .109 | 35.742 | 1 | .000 | 1.924 | 1.552 | 2.384 |
| | [D=6.00] | .182 | .101 | 3.240 | 1 | .072 | 1.199 | .984 | 1.462 |
| | [D=7.00] | 0(b) | . | . | 0 | . | . | . | . |
| | [H=1.00] | -.199 | .096 | 4.337 | 1 | .037 | .819 | .679 | .988 |
| | [H=2.00] | -.296 | .097 | 9.218 | 1 | .002 | .744 | .614 | .900 |
| | [H=3.00] | -.271 | .107 | 6.387 | 1 | .011 | .762 | .618 | .941 |
| [H=4.00] | -.167 | .091 | 3.384 | 1 | .066 | .846 | .709 | 1.011 | |
| [H=5.00] | 0(b) | . | . | 0 | . | . | . | . | |

a The reference category is: Unpicked.

b This parameter is set to zero because it is redundant.

Architectural Cue Model in Evacuation Simulation for Underground Space Design

| Classification | | | |
|--------------------|-----------|--------|-----------------|
| Observed | Predicted | | |
| | Unpicked | Picked | Percent Correct |
| Unpicked | 2283 | 1153 | 66.4% |
| Picked | 1083 | 2851 | 72.5% |
| Overall Percentage | 45.7% | 54.3% | 69.7% |

Appendix G Estimated Curves of the Ratio-Probability Distributions

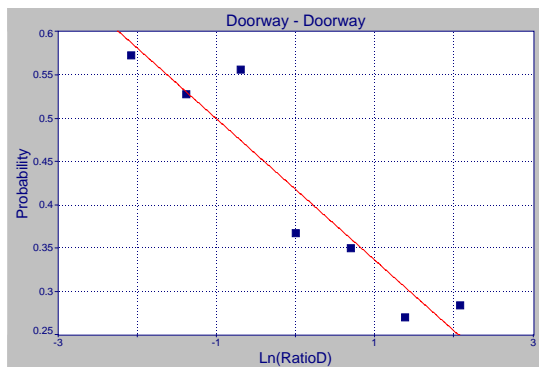
In this appendix, there are two sets of estimations for the Ratio-Probability distributions. In the first set, the estimations are based on a line function. In the second set, the estimations are based on a growth function.

G.1 Estimations for the line function

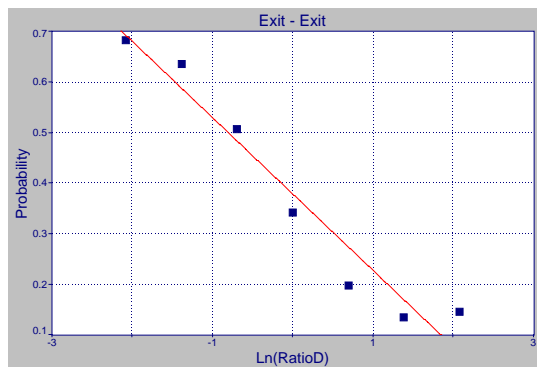
To support the analysis on the general trends of the Ratio-Probability distributions, the scattered points are estimated into the line function for every variable in every cue pair. These lines are classified according to the variable related to them. In the caption of the figures, the cue pair type is annotated first. Following it there is an expression like Line(a, b), which indicates the two parameters of the line function (Eq. G-1). In the end of the caption the r^2 value of the estimation is provided.

$$Y = aX + b \quad (G-1)$$

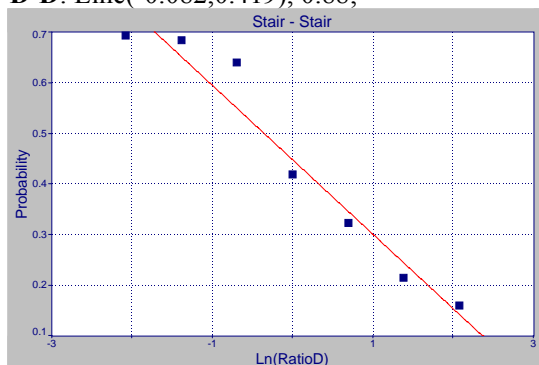
G.1.1 Estimated line function of RatioD



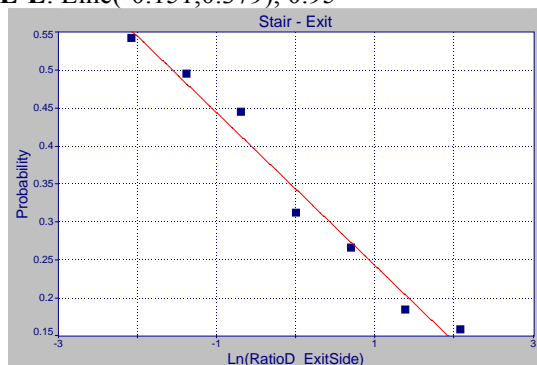
D-D: Line(-0.082,0.419), 0.88;



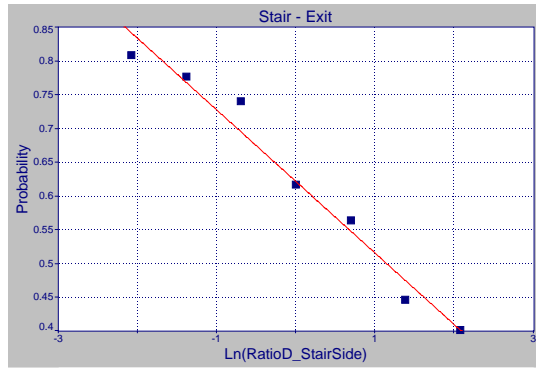
E-E: Line(-0.151,0.379), 0.95



S-S: Line(-0.147,0.449), 0.95;

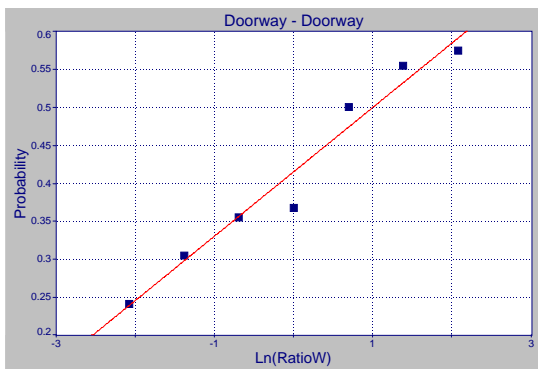


S-E(Exit Side): Line(-0.101,0.344), 0.98

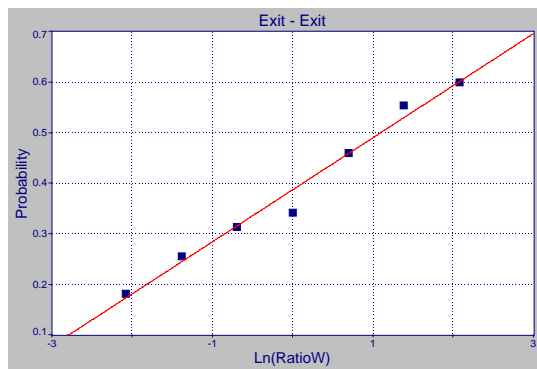


S-E(Stair Side): Line(-0.106,0.623), 0.97;

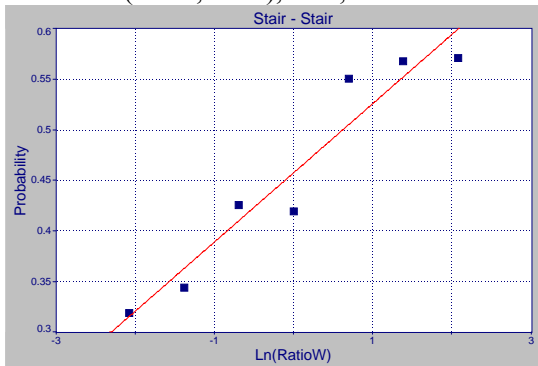
G.1.2 Estimated line function of RatioW



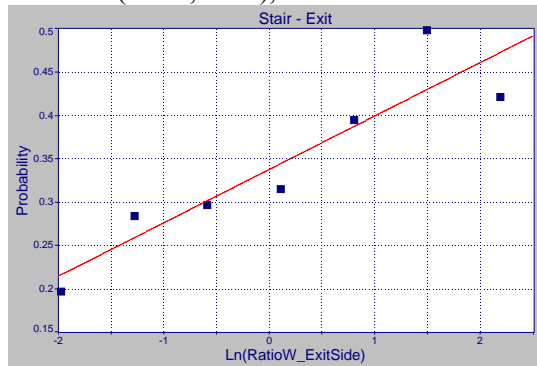
D-D: Line(0.085,0.415), 0.96;



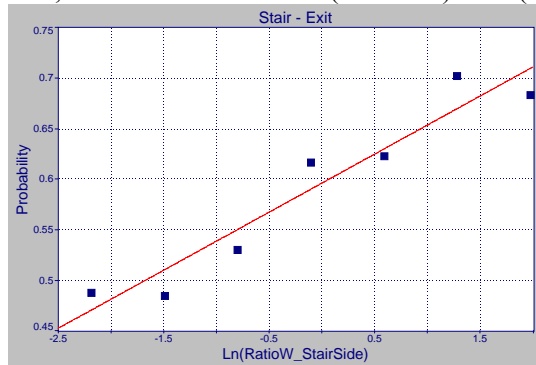
E-E: Line(0.103,0.387), 0.98



S-S: Line(0.068,0.457), 0.92;

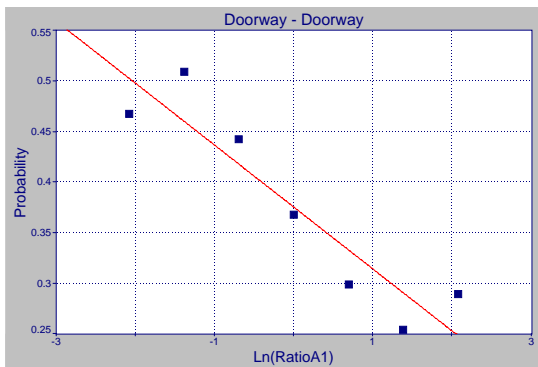


S-E(Exit Side): Line(0.062,0.338), 0.85

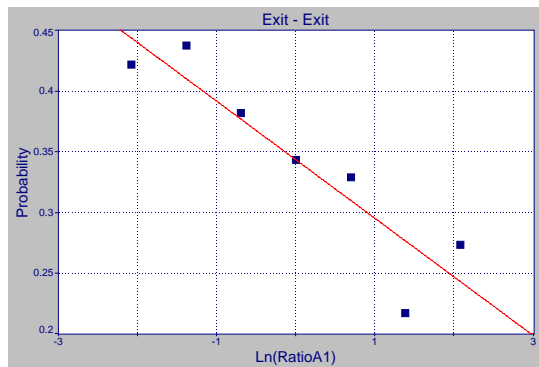


S-E(Stair Side): Line(0.058,0.596), 0.92;

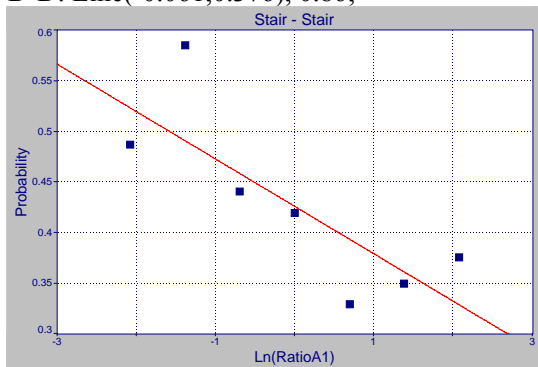
G.1.3 Estimated line function of RatioA1



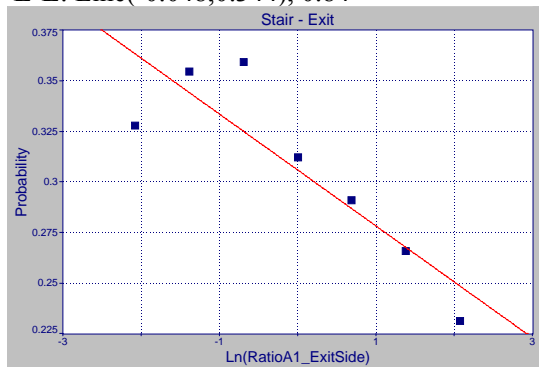
D-D: Line(-0.061,0.376), 0.86;



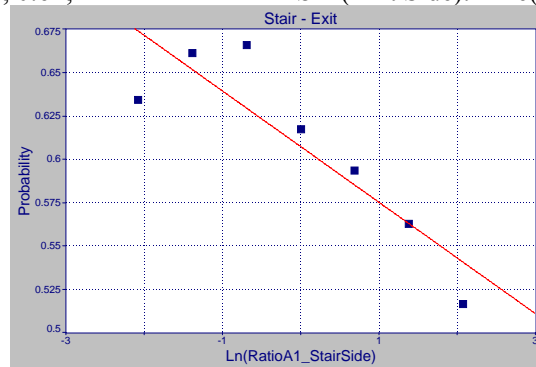
E-E: Line(-0.048,0.344), 0.84



S-S: Line(-0.047,0.427), 0.64;

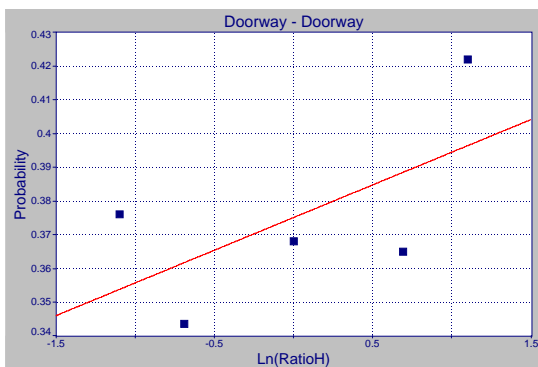


S-E(Exit Side): Line(-0.028,0.306), 0.78

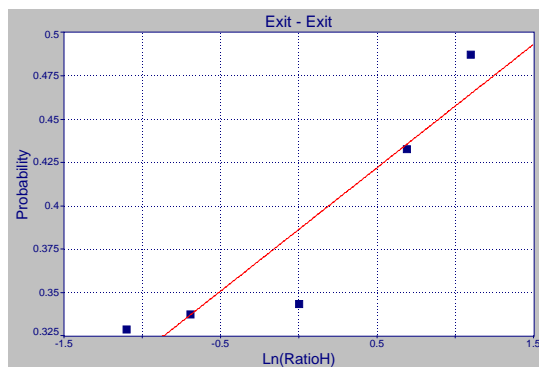


S-E(Stair Side): Line(-0.032,0.608), 0.79

G.1.4 Estimated line function of RatioH

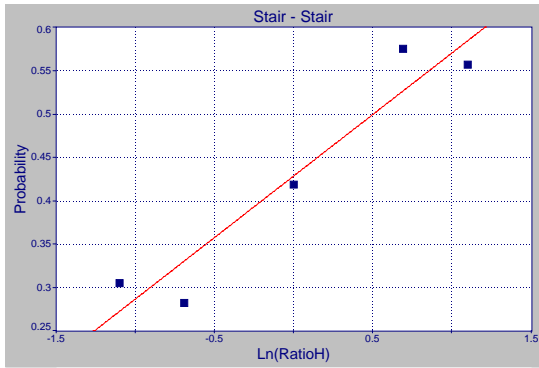


D-D: Line(0.019,0.375), 0.38;

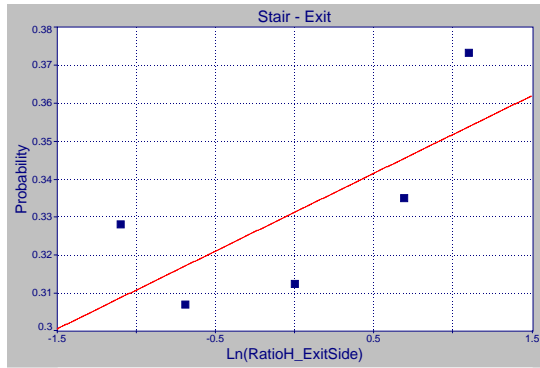


E-E: Line(0.071,0.386), 0.86

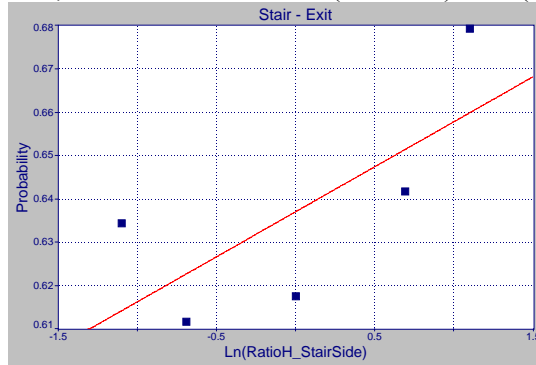
Architectural Cue Model in Evacuation Simulation for Underground Space Design



S-S: Line(0.142,0.428), 0.91;

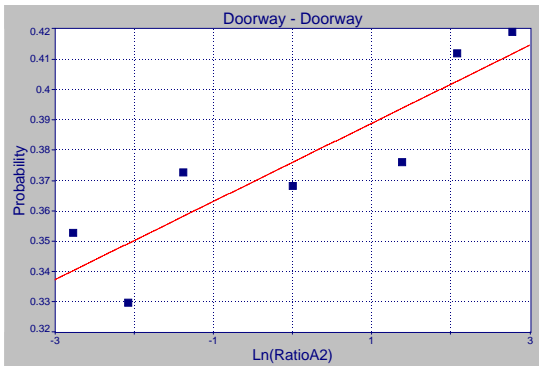


S-E(Exit Side): Line(0.021,0.331), 0.52

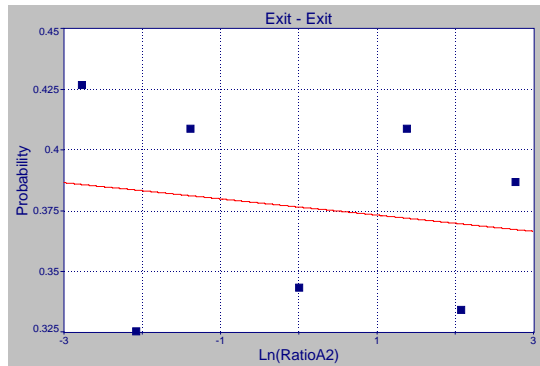


S-E(Stair Side): Line(0.021,0.637), 0.51

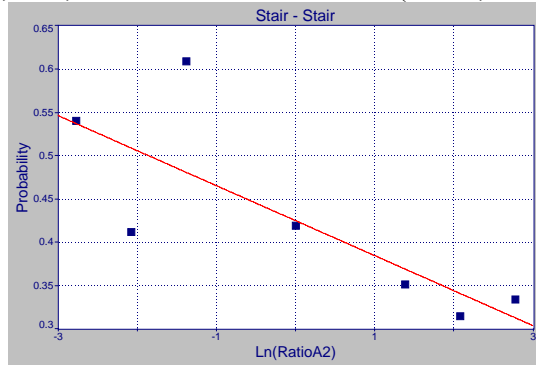
G.1.5 Estimated line function of RatioA2



D-D: Line(0.013,0.376), 0.78;



E-E: Line(-0.003,0.377), 0.03



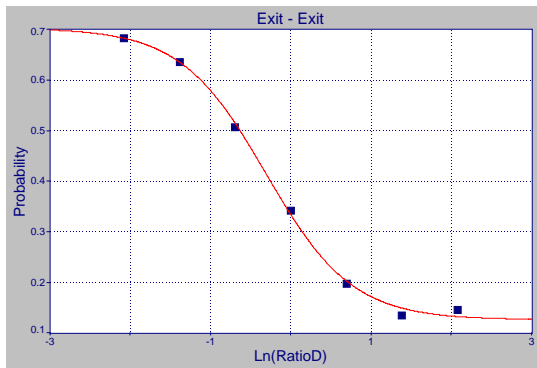
S-S: Line(-0.041,0.426), 0.63

G.2 Estimations for the growth function

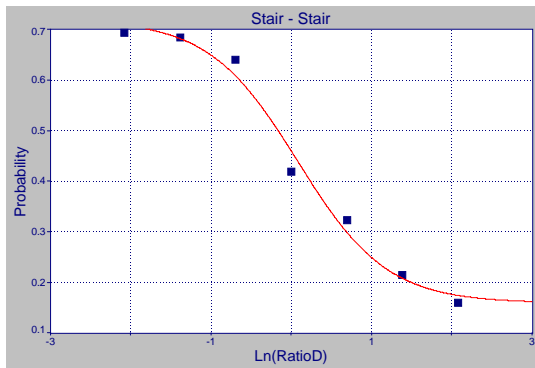
To support the analysis on the nonlinear feature of the Ratio-Probability distributions, some scattered points are estimated into the growth function when the r^2 value can be higher than 0.95. These growth functions are classified according to the variable related to them. In the caption of the figures, the cue pair type is annotated first. Following it there is an expression like Growth(a, b, c, d), which indicates the four parameters of the function (Eq. G-2). In the end of the caption the r^2 value of the estimation is provided.

$$Y = \frac{a}{1 + e^{bX+c}} + d \quad (G-2)$$

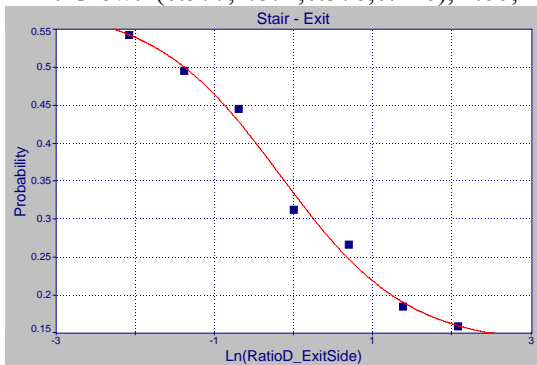
G.2.1 Estimated growth function of RatioD



E-E: Growth(0.577,1.874,0.576,0.126), 1.00;



S-S: Growth(0.560,1.801,-0.143,0.160), 0.99

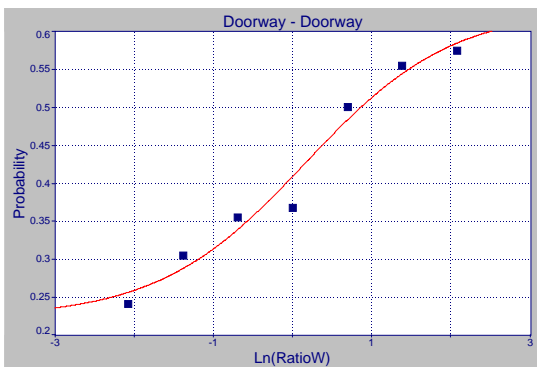


S-E(ExitSide): Growth(0.447,1.251,0.196,0.134), 0.99;

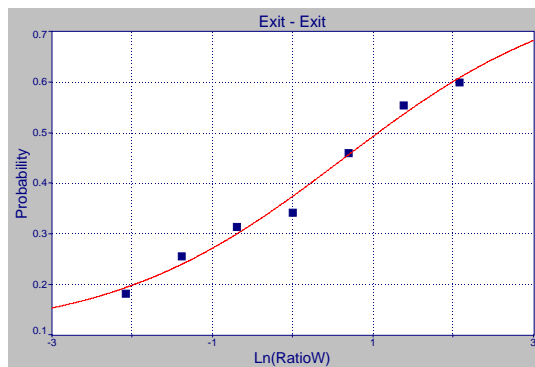


S-E(Stair Side): Growth(0.501,1.149,-0.435,0.337), 0.99

G.2.2 Estimated growth function of RatioW

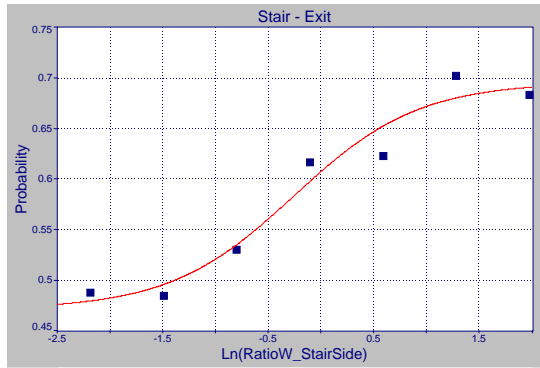
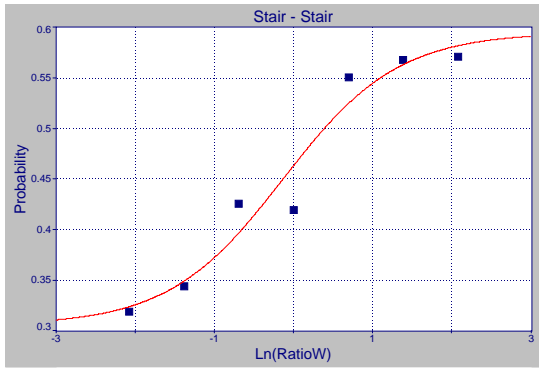


D-D: Growth(-0.408,1.078,-0.185,0.631), 0.97;



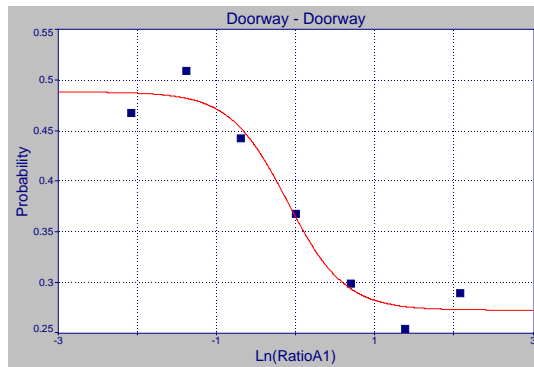
E-E: Growth(-0.696,0.688,-0.431,0.796), 0.99

Architectural Cue Model in Evacuation Simulation for Underground Space Design



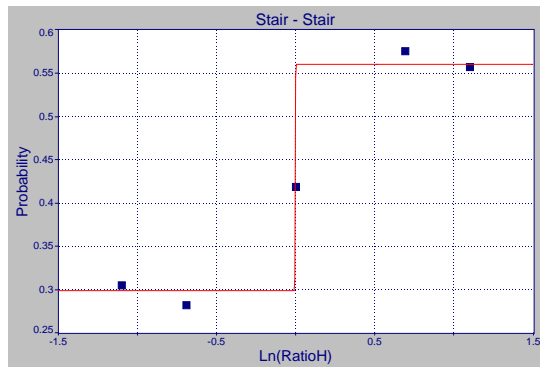
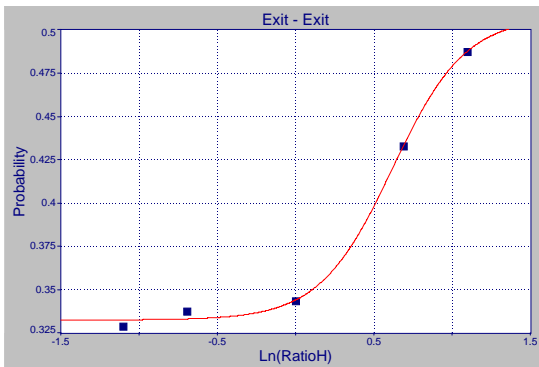
S-S: Growth(-0.290,1.380,0.168,0.595), 0.95; S-E(Stair Side): Growth(-0.225,1.693,0.422,0.696), 0.96

G.2.3 Estimated growth function of RatioA1



D-D: Growth(0.216,2.76,0.277,0.273), 0.97

G.2.4 Estimated growth function of RatioH



E-E: Growth(-0.175,4.285,-2.676,0.508), 1.00; S-S: Growth(0.261,-86.527,-0.723,0.295), 0.96

Author Index

- Acking, 50
Aguirre, 25, 42, 162
Al-Kaisy, 25
Allen, 12
Antonini, 117
Arentze, 33, 34, 112
Arthur, 2, 4, 12, 14, 15, 17, 19, 20, 23, 25, 28,
30, 31, 32, 37, 48
Asch, 25
Ashihara, 56, 95
Augenbroe, 5
Bailenson, 50, 53
Banks, 53
Barker, 53
Baskaya, 29
Bateson, 50, 53
Baum, 26
Beall, 51
Bell, 51
Berlin, 40
Bickman, 40
Bierlaire, 117
Blascovich, 51
Bockholts, 17
Bolhner, 14
Book, 16
Bovy, 24, 34, 47, 49, 50, 130
Bradley, 49
Breaux, 40
Breiman, 24
British Standards Institution, 17, 147
Brosamle, 14
Bruno Zevi, 36
Brunswick, 19
Bryan, 2, 19, 30, 40
Bulthof, 54
Bulthoff, 130
Burigat, 130
Buxbaum, 130
Canter, 19, 40, 48, 50, 53
Carassa, 130
Carmody, 2, 37
Carpman, 8, 12, 13, 14, 17, 23, 32
Cattin, 54
Chauvet, 5
Cheung, 30
Ching, 27, 36
Chittaro, 130
Choi, 29
Churchill, 26
Corbusier, 27
Crosby, 19
Cubukcu, 130
Cutting, 22, 52, 54, 56, 57
da Vinci, 19
Daamen, 24, 48
Dalton, 30, 54
de Kort, 53
de Vries, 51, 53, 62, 66
Deasy, 8, 32
Dijkstra, 7, 51, 53, 54, 55, 66
Dogu, 16
Drager, 42, 162
Edelman, 40
Egenhofer, 15, 16, 31
Ellis, 53
Epstein, 16
Erkip, 16
Evans, 47, 48
Farkas, 18, 25, 47
Feigenbaum, 130, 131
Feinberg, 17, 54
Ferwerda, 54
Foreman, 51
Francis, 36
Frank, 14
Freeman, 51
Friedman, 56
Fritz, 18
Galea, 19
Garling, 16, 55
Geminiani, 130
Gestalt, 48
Gibson, 4, 19, 20, 21
Gigerenzer, 19, 35
Gilinsky, 56
Gluck, 16
Goldblatt, 130
Goldfarb, 53
Golledge, 4, 12, 16, 20, 28, 38, 55
Gombrich, 50
Gooch, 53
Gopal, 16
Graat, 17

Architectural Cue Model in Evacuation Simulation for Underground Space Design

- Grant, 8, 12, 13, 14, 17, 23, 32
Green, 54
Greenberg, 54
Gudowskil, 24
Gwynne, 41
Haight, 24
Hair, 55
Halcrow, 24
Hall, 19, 24, 32, 56, 57
Hamacher, 34
Hankin, 24
Heim, 51
Helbing, 18, 20, 25, 47, 131
Henik, 49
Hensen, 5
Henson, 56
Hershberger, 20, 21, 26
Hershenson, 56, 57
Hillier, 4, 26, 29
Hochmair, 14
Holl, 95
Holscher, 14
Hoogendoorn, 20, 24, 34, 48
Hopfe, 5
Hostikka, 18, 25, 42, 45, 147, 162
Hu, 53
Hui, 50, 53
IJsselsteijn, 51, 54
International Code Council, 65, 147
Ittelson, 22, 48, 57
Jansen-Osmann, 130
Janzen, 54, 130
Johnson, 17, 26, 54
Kaufman, 174
Kline, 53, 54
Klingsch, 135
Knauff, 14, 130
Kobes, 12, 130
Kotek, 5
Kraiss, 51, 53
Kretz, 42, 162
Kroes, 49
Kuhlen, 51, 53
Kuipers, 4, 16, 29
Kukla, 24
Kuligowski, 24, 41, 42, 45, 131, 135, 147, 162
Kuller, 50
Lage, 25
Lam, 21, 22, 30, 31, 57
Lang, 47
LaPorta, 5
Lasswell, 8, 32
Lawson, 8, 26, 30, 31, 32, 95
Leiser, 16, 49
Lerup, 40
Lin, 2, 5, 54
Lindberg, 16
Lombard, 50, 53
Loomis, 51
Lovas, 24, 42, 162
Low, 40
Luttich, 14
Lym, 32
Lynch, 4, 12, 16, 19, 28, 29, 32
Maguire, 130
Marks, 18
Matuszyk, 24
McCalla, 16
McDaniel, 40
McDermott, 16
Meancham, 2, 17, 18, 65, 148
Meilinger, 14, 130
Menges, 53
Midden, 17
Ministry of Housing and Urban-Rural Development of the People's Republic of China, 95, 147
Moitoza, 174
Montello, 12
Montgomery, 39, 55, 96
Morganti, 130
Moscovici, 25
Murakami, 54
Murray, 52
Naffrechoux, 25
Nasar, 130
Nash, 53, 54
Nassar, 25
National Fire Protection Association, 65
Netsch, 36
Newman, 130
Noman, 15
Norberg-Schulz, 36
O'Malley, 53
O'Neill, 16, 26, 29
Omer, 130
Oppewal, 54, 55
Orzechowski, 34, 55
Ozcan, 29

- Ozel, 4, 17, 18, 19, 30, 31, 32, 40, 41, 42, 47,
130, 131, 162, 173
Pallasmaa, 95
Pan, 42, 45, 135, 162
Papamichael, 5
Passini, 2, 3, 4, 12, 14, 15, 17, 19, 20, 23, 25,
27, 28, 29, 30, 31, 32, 37, 48
Pazzaglia, 130
Peacock, 24, 41, 42, 45, 131, 147, 162
Penn, 20, 29, 30, 117, 173, 174
Peponis, 29
Perez-Gomez, 95
Pertaub, 53
Plokker, 5
Porter, 57
Rapoport, 8, 22, 23, 26, 32
Raubal, 15, 16, 31, 131
Regan, 48, 57
Richards, 50
Riecke, 54
Rogers, 50, 53, 56
Rogsch, 135
Rose, 51
Sadeghian, 130
Santos, 25, 42, 162
Sas, 12
Savannah Simulations AG, 42, 162
Schadschneider, 25
Schindler, 4, 28, 29, 54
Schreckenber, 42, 162
Scott, 50
Seidel, 16
Seyfried, 135
Shafer, 50
Sheldon, 49
Shih, 2, 5, 54
Sime, 18, 19, 40, 47
Slater, 53
Spiers, 130
Spring, 50
Srinivasan, 54
Stahl, 40
Stamps, 50, 53
Steffan, 51, 53
Sterling, 2, 37
Stern, 34, 47, 49, 50, 130
Still, 24
Strubea, 14
Struck, 5
Stytz, 53
Sun, 62, 66
Sutherland, 174
Tan, 51, 52, 53
Taylor, 130
Timmermans, 7, 33, 34, 51, 53, 54, 55, 112
Tjandra, 34
Tlauka, 130
TNO, 50
Tolman, 28
Tubbs, 2, 17, 18, 65, 148
Turner, 20, 29, 30, 117, 173, 174
Tzelgov, 49
Ulrich, 50, 53
Valins, 26
Van Veen, 54
Verhulst, 112
Verlander, 34
Vicsek, 18, 25, 47
Vishton, 22, 52, 54, 56, 57
Vrachliotis, 14
Vriens, 55
Wanger, 54
Was, 24
Weidmann, 24
Weisman, 13, 14, 15, 16, 19, 26, 27, 28, 29
Werner, 4, 28, 29, 54
Wiedenbauer, 130
Wiklund, 42, 162
Willemsen, 53
Wilson, 29, 53
Wineman, 29
Witmer, 53, 54
Wittink, 54
Wood, 19
Wools, 50
Worboys, 16, 31, 131
Wright, 24
Wurzberg, 48
Xia, 15
Xie, 25
Yang, 2, 5, 54
Zevi, 26
Zimring, 29, 31, 48

Dutch Summary

Dit proefschrift presenteert een simulatiemodel van het vluchtproces waarin de evacué zijn weg naar de veiligheid zoekt aan de hand van fysiek ruimtelijke indicaties die aanwezig zijn in het bouwkundige ontwerp van een complexe ondergrondse omgeving.

Als gevolg van de snel groeiende verstedelijking, moeten de metropolen nieuwe ondergrondse transport netwerk ontwikkelen. Iedere knoop in zo'n netwerk bestaat uit een ondergronds station met verbindingen met de omliggende ondergrondse winkelgebieden, die een publieke functie vervullen en een complexe ruimtelijke organisatie hebben. Bij het ontwerp van zo'n complexe publieke ondergrondse ruimte, hebben de prestatie gebaseerde evaluatiemethoden met computer evacuatiesimulaties, de traditionele voorschrijvende en regelgeving gebaseerde methoden vervangen. Echter, door een beperkt begrip van de invloed van de ruimte op het zoekgedrag van de evacué naar de vluchtroute, hebben architecten nog steeds geen goed gereedschap voor het ruimtelijk ontwerp. Het ruimtelijk ontwerp is een fundamenteel onderdeel van het totale ontwerpproces en de belangrijkste taak van de architect. Het onderzoek in dit proefschrift wil een duidelijk inzicht geven in het ruimtelijk ontwerp gebaseerde zoekproces naar de vluchtroute, en er wordt een simulatiemodel gepresenteerd voor de evaluatie van het ruimtelijk ontwerp van een complexe ondergrondse omgeving.

In de literatuur wordt het zoekgedrag naar een vluchtroute opgevat als een special geval van het zoeken van een route in een onbekende omgeving. De evacué zoekt zijn vluchtroute waarbij hij bij elke stap beslissingen neemt. Bij elke stap identificeert hij de fysiek ruimtelijke indicaties binnen zijn gezichtsveld, kiest op basis van zijn inschatting de indicatie met de hoogste waarschijnlijkheid die naar de veiligheid leidt en verplaatst zich vervolgens in de richting van de gekozen indicatie.

Aan de hand van de hiervoor beschreven theorie, zijn verschillende methoden gebruikt om het simulatiemodel te ontwikkelen. Ten eerste zijn enquêtes gebruikt om te onderzoeken welke elementen uit de fysiek ruimtelijke omgeving door evacués worden waargenomen als locale indicatie in de context van dit onderzoek. Ten tweede is een CAVE opstelling gebouwd om observaties te doen over het virtuele evacuatie gedrag, om kennis te verzamelen over de beslissingsregels die worden toegepast bij locale fysiek ruimtelijke indicaties. Ten derde is de architectuur voor het simulatiemodel van het route zoekproces opgesteld. Ten vierde is een CAVE gebaseerde conjuncte meetmethode toegepast, om de voorkeursfunctie te bepalen die de kwalitatieve conclusies met betrekking tot de fysieke ruimtelijke indicaties vertaald naar kwantitatieve variabelen die het simulatiemodel aansturen. Ten slotte, op basis van alle voorgaande resultaten is het computer programma SpaceSensor ontwikkeld.

Samenvattend, heeft dit onderzoek een nieuw simulatiemodel voor vluchtgedrag opgeleverd dat wordt gestuurd door fysiek ruimtelijke indicaties. Het draagt bij aan de evaluatie van ruimtelijke ontwerpen van complexe ondergrondse omgevingen door de architect door middel van simulatie van het zoekgedrag naar de vluchtroute en door de toepassing van een hierop gebaseerd bouwkundige veiligheids criterium (LEEI). Bovendien dragen alle kwantitatieve gegevens over het zoekgedrag naar de vluchtroute ook bij aan het begrip over de invloed van het ruimtelijk ontwerp op evacuatiegedrag.

Curriculum Vitae

Chengyu Sun was born in 1978 in Shanghai, China. He studied Architecture in College of Architecture and Urban Planning, Tongji University, Shanghai, China. In 2002, he received his Bachelor's degree with a graduate design project on future spaces. Afterwards, he studied Architectural Design and Theories in Tongji University and graduated on a master thesis about the evolutionary architectural design method and tool in 2005. From April 2005, he was appointed as an assistant professor in Tongji University, worked as a part time architect, and started his part time PhD project in Design System group of Technology University Eindhoven, the Netherlands.

In his teaching practices, he was interested in the digital design methods, especially writing design by codes. With his exploration in this field mainly reflected by his Chinese publications, he was appointed as a lecturer of Tongji University in 2007.

In his architecture practices, he used the summer and winter vocations to explore his design concepts in China. He was the team leader in the preliminary design of Shanghai Conservatory of Music Project, in which his design won the competition from the other famous architects, such as Jean-Marie Charpentier. Collaborating with other architects, he designed small-scale projects in several provinces of China, such as Eco Rural Village School Project (Liaoning Province), Rangers' Office & College Project (Jiangxi Province), Li Zhuang Coach Station Project (Sichuan Province), and Xi Tang Tongji Club Project (Zhejiang Province).

In his PhD research, he explored the fundamental aspect of architectural design, namely the space manipulation. He is the first author of 8 conference papers in English and 3 journal papers in Chinese. Now, his research interests are: human behavior in architectural space / virtual environment, building performance simulation based architectural design, and digital design methods. His email is: cy.sun@tongji.edu.cn