Individual Differences in Navigating and Experiencing Presence in Virtual Environments

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List of Abbreviations

3D	3 Dimensional
2D	2 Dimensional
AI	Artificial Intelligence
ANN	Artificial Neural Network
AR	Augmented Reality
BDI	Belief Desire Intention
CAVE	Cave Automatic Virtual Environment
CIS	Creative Imagination Scale
CSA	Cognitive Styles Analysis
DV	Dependent Variables
E	Extroversion Type
ECHOES	EduCational Hypermedia OnlinE Systems
F	Feeling Type
FIPA	Foundation for Intelligent Physical Agents
HCI	Human–Computer Interaction
HMD	Head Mounted Display
I	Introversion Type
IV	Independent Variables
J	Judging Type
LRS	Landmark Route Survey
LVQ	Learning Vector Quantisation
MBTI	Myers-Briggs Type Indicator
MR	Mixed Reality
N	Intuition Type
P	Perceving Type
PDP	Parallel Distributed Processing
RNN	Recurrent Neural Network
S	Sensing Type
SOM	Self-Organising Map
SSH	Spatial Semantic Hierarchy
SUS	Slater, Usoh and Steed Questionnaire
T	Thinking Type
TAS	Tellegen Absorption Scale
UCD	User-Centred Design
VE	Virtual Environment
VR	Virtual Reality
VRML	Virtual Reality Modelling Language

Abstract

The effort of making Virtual Environments (VEs) more useful and satisfactory to use lie at the core of usability research. Because of their development and widespread accessibility, VEs are being used by an ever-increasing diversity of users, whose individual differences impact on both task performance and level of satisfaction. This aspect raises a major challenge in terms of designing *adaptive* VEs, suitable not for the *average user* but for each individual user. One way to address this challenge is through the study of individual differences and their implications, which should lead to new effective ways to accommodate them.

Adaptivity reflects the system's capability to automatically tailor itself to dynamically changing user behaviour. This capability is enabled by a user model, acquired on the basis of identifying the user's patterns of behaviour.

This thesis addresses the issue of studying and accommodating individual differences with the purpose of designing adaptive VEs. The individual differences chosen to be investigated are those that impact particularly on two fundamental aspects underlying each interaction with a VE, namely navigation and sense of presence. Both these aspects are related to the perceived usability of VEs.

The impact that a set of factors like empathy, absorption, creative imagination and willingness to be transported within the virtual world has on presence has been investigated and described through a prediction equation. Based on these findings, a set of guidelines has been developed for designing VEs able to accommodate these individual differences in order to support users to experience a higher level of presence.

The individual differences related to navigation within VE have been investigated in the light of discriminating between efficient versus inefficient search strategies. Building a user model of navigation affords not only a better understanding of user spatial behaviour, but also supports the development of an adaptive VE which could help low spatial users to improve their navigational skills by teaching them the efficient navigational rules and strategies.

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Finally, I thank God for sanity, strength and inspiration. His continual blessing helps me to search for the best in myself and in the others.

Declaration

I declare that this thesis is my own work and has not been submitted in any form for another degree or diploma at this, or any other, University or institute of tertiary education.

Corina Sas
15 January 2004

Associated Publications

The following publications have arisen directly as a result of the research described in this thesis.

- Sas, C., O'Hare, G. and Reilly, R. (2004). Virtual environment trajectory analysis: A basis for navigational assistance and scene adaptivity. *Future Generation Computer Systems*, Special Issue on "Interaction and Visualisation Techniques for Problem Solving Environments", Elsevier Press (in press).
- Sas, C. and O'Hare, G. (2003). Presence equation: An investigation into cognitive factors underlying presence. *Presence: Teleoperators and Virtual Environments* 12(5), MIT Press, p. 523–537.
- Sas, C., O'Hare, G. and Reilly, R. (2003). Presence and task performance: An approach in the light of personality cognitive style. *International Journal of Cognition Technology and Work.* Special Issue on "Presence: design and technology challenges for cooperative activities in virtual or remote environments", Elsevier Press (in press).
- Sas, C., Reilly, R., O'Hare, G., Marian, I. and Mangina, E. (2003). Modelling user navigation. Special Issue of the World Scientific and Engineering Academy and Society (WSEAS) *Transactions on Systems*, 3(2), p. 582–588.
- Sas, C. (2001). Acquiring spatial knowledge: An experiment in virtual environment. International Association for People–Environment Studies, *Bulletin of People–Environment Studies*, 20, p. 10.
- O'Hare, G., Sas, C. and Byrne, C.A. (2001). Agent mediation and management of virtual communities: A redefinition of the traditional community concept. In *Proceedings of IEEE International Conference on Systems, Man and Cybernetics (SMC'01)*, IEEE Computer Society Press.
- Sas, C., O'Hare, G.M.P. and Reilly, R. (2004). A Performance Analysis of Movement Patterns. International Conference on Computational Science, Workshop on Scientific Visualisation and Human-Machine Interaction in a Problem-Solving Environment. In *Lecture Notes in Computer Science.* Springer-Verlag (in press).
- Sas, C., O'Hare, G. and Reilly, R. (2003). On-line trajectory classification. International Conference on Computational Science, Workshop on Scientific Visu-

alisation and Human-Machine Interaction in a Problem-Solving Environment. In *Lecture Notes in Computer Science* 2659 (p. 1035–1044). Springer-Verlag.

- Sas, C., O'Grady, M. and O'Hare, G.M.P. (2003). Electronic navigation—Some design issues. Fifth International Symposium on Human Computer Interaction with Mobile Devices and Services. In *Lecture Notes in Computer Science* 2795 (p. 471–475). Springer-Verlag.
- Sas, C. and O'Hare, G. (2003). Impact of cognitive style upon sense of presence. In J. Jacko and C. Stephanidis (eds.), *Proceedings of the 10th International Conference on Human–Computer Interaction* (p. 696–700). Mahwah: Lawrence Erlbaum Associates.
- Sas, C., O'Hare, G. and Reilly, R. (2003). A connectionist model of human navigation. In *Proceedings of the 7th International Conference on Cognitive and Neural Systems* (p. 89). Boston: Boston University Press.
- Sas, C., O'Hare, G. and Reilly, R. (2003). A connectionist model of spatial knowledge acquisition in a virtual environment. In S.A. Macskassy, R. Wilkinson, A. Goker and M. Bauer (eds.), The 9th International Conference on User Modeling, *Proceedings of Workshop on User Modeling, Information Retrieval and Machine Learning* (p. 40–47).
- Sas, C. and Reilly, R. (2003). Extracting a spatial grammar from recurrent neural network. The 7th Neural Computation and Psychology Workshop.
- Sas, C. and O'Hare, G. (2002). Presence and individual differences in virtual environment: Usability study. In H. Sharp, P. Chalk, J. LePeuple, J. Rosbottom (eds.), *Proceedings of 16th British HCI Conference* Vol. 2 (p. 50–53). London: British Computer Society.
- Sas, C., O'Hare, G. and Byrne, C. (2002). Navigation in 3D non-immersive virtual reality: A usability study. In N. Callaos, M. Bica, M. Sanchez (eds.), *Proceedings of the 6th World Conference on Systemics, Cybernetics and Informatics* (p. 30–34) Orlando, FL: International Institute of Informatics and Systemics.
- Sas, C., O'Hare, G. and Reilly, R. (2002). A connectionist approach to modelling navigation: Trajectory self organization and prediction. In N. Carbonell and C. Stephanidis (eds.), *Proceedings of 7th ERCIM Workshop: User Interfaces for All* Vol. XII (p. 111–116). Chantilly: ERCIM.
- Sas, C. and O'Hare, G. (2001). The presence equation: An investigation into cognitive factors underlying presence within non-immersive virtual environments. The 4th Annual International Workshop on Presence.
- Sas, C., Reilly, R. and O'Hare, G.M.P. (2001) Virtual Reality in Surgery: Between Satisfaction and Stress. In A. Riegler, M.F. Peschl, K. Edlinger, G. Fleck and W. Feigl (eds.), *Virtual Reality. Cognitive Foundations, Technological Issues, and Philosophical Implications* (p. 99–111). Frankfurt/M.: Peter Lang Verlag.

To my parents:
Ioan and Elena

Chapter 1

Introduction

The explosive growth of Information Technology has enabled an ever-increasing number of users to perform a large variety of computer-mediated activities, serving the goals of working, learning or playing. The wide diversity characterising these users in terms of backgrounds, skills, interests, motivations, expertise and learning style has started to challenge the traditional way of delivering computer technology. Universal Usability requires that software systems accommodate a diverse set of users (Shneiderman, 2000), since no single interface is capable of satisfying every user (Kules, 2000). Adaptive systems, able to monitor user's activity and automatically adjust themselves to accommodate such user individual differences, seem to provide a promising solution to this problem (Savidis et al., 1997; Jameson, 2003).

Given its infancy and inherent complexity, the advent of Virtual Reality (VR) technology puts additional strains on adaptivity. The major goal of this thesis is to improve the understanding of how adaptive Virtual Environments (VEs) should be designed in order to accommodate the individual differences of their users.

The work carried out in this thesis targets two fundamental aspects underlying almost every interaction with a VE, namely the sense of presence experienced by users and their spatial behaviour. The sense of presence, or so-called *sense of being there* (inside the virtual world), is a psychological side effect of any mediated experience. Probably the most common form of spatial behaviour defined as a "behaviour that occurs in response to the spatially distributed nature of the environment" (Ungar, 2003), is navigation. *Navigation* is a complex and challenging activity, even when it is performed in the physical world. In addition, studies have shown that navigational tasks performed within VEs put unusual demands on their users (Waller, 2000).

Both these aspects are relevant, because of their prevalence and of their impact on user's interaction with VEs. Central to the latter is the concept of *usability*, which lies at the core of the design of any artefact. A well designed VE is intuitive, easy to use, enables a smooth learning curve and therefore allows users to successfully accomplish the required tasks. In addition, it is expected to provide a good degree of satisfaction, which characterises any enjoyable experience.

A great deal of research has been concerned with technological factors that could influence the usability of VEs. In contrast, the impact of human factors on the perceived usability of a system has been less well addressed. The lack of such studies is even more significant when it comes to VEs (Waller, 2000). This thesis aims to address this shortcoming. It focuses on *individual differences* related to performance on navigational tasks and to the degree of sense of presence experienced by the users. The study findings indicate that the concept *one size fits all* is obsolete when it comes to the design of VEs.

1.1 Individual Differences

Individual differences is an umbrella term used to describe an entire field of research, primarily involving psychology, that focuses on aspects of behaviour that differentiate individuals from one another. Clinical studies involve an in depth investigation of one or a limited number of subjects in order to highlight their individual unique profile. There is, however, a more general approach to studying individual differences. This approach, and the one taken by this thesis, strives to capture *dimensions* of individual differences rather than individual patterns. Accordingly, one can group subjects together, based on the commonly shared variance with respect to a particular aspect of their individuality.

Such an approach leads to the identification of differences among groups of subjects (inter-group differences) as opposed to the differences among individuals within the same group (intra-group differences). Grouping subjects in clusters according to some criteria offers a better understanding of the relevant aspects of the phenomenon by reducing the amount of data, while at the same time preserving the amount of information (Lorr, 1983).

The study of individual differences can be pursued in three areas (Revelle, 2000) which have been addressed in this thesis:

- Identifying, and consequently describing groups of individuals sharing common features, is only a preliminary stage in this kind of research. It leads to a descriptive taxonomy of those factors which underlie the individual differences.
- Attempts to highlight a causal relationship between these factors which underlie the individual differences and other relevant aspects on which they impact constitute another area of research in this field. A significant outcome of such studies consists in the predictive validity of their findings.
- The third area of research in this field is a theoretical one, aiming to explain the structure and dynamics of individual differences.

1.2 Motivation

The ultimate goal when studying individual differences is to enhance system usability. Once they have been identified, and if their impact is found to be significant, efforts should be made to accommodate them. Properly accommodated, these individual differences should lead to higher task performance and increased user satisfaction. Apart from their practical interest, an additional benefit of studying individual differences resides in providing a framework for understanding them.

This work focuses on two major aspects which usually describe any interaction with a VE:

- navigation, and
- sense of presence.

Because of its prevalence, there is a tendency to take the navigational process for granted. However, navigation is a complex activity which requires seamless integration of several cognitive processes. The difficulties associated with navigation become especially obvious when it is performed in unfamiliar environments (i.e. one becomes lost). Due to their specific characteristics, VEs put additional demands on untrained users (see Chapter 2). Fortunately, the adaptive versions of such VE systems have the potential of adapting themselves in order to accommodate individual differences which impact on users' performance on spatial tasks.

Most studies focusing on navigation have addressed the issue of individual differences with respect to navigation in abstract information space, such as hypermedia space or semantic space (Chen and Ford, 1997; Chen, 2000; Brusilovsky and Maybury, 2002). In contrast, less research has been carried out in the area of human spatial navigation within VEs. The potential of VEs for training spatial skills has been extensively acknowledged, but little work has been carried out on the potential use of VEs for training basic spatial abilities (Durlach et al., 2000).

The work presented in this thesis focuses on accommodating the individual differences reflected in navigational patterns. The ability to succeed in navigational tasks, of any kind, depends on how humans understand space. This involves an implicitly developed representation of the spatial layout, usually in the form of so-called *cognitive maps*. Despite its significance, the process of accessing such representations raises difficulties. In an attempt to overcome these limitations, this thesis proposes original alternative methods, inspired by the tools and techniques developed in the area of machine learning.

The individual differences in experiencing presence, a psychologically related phenomenon experienced by users while they interact with virtual reality systems, have been hypothesised by the presence literature, but no experimental study has been undertaken. In this thesis, some individual differences in experiencing presence are identified and their value for understanding and predicting presence is discussed. Based on such individual differences, this work seeks to examine how these may be used for improving the design of VEs in order to increase presence or performance on spatial tasks.

Figure 1.1 presents the interrelationships between these major areas: navigation and sense of presence approached through the study of individual differences, for increasing the usability of desktop VEs. Providing guidelines for designing adaptive VEs in order to accommodate such individual differences is the final aim of the work presented in this thesis. Figure 1.1 also suggests the niche occupied by the thesis in the context of the previously mentioned research fields.

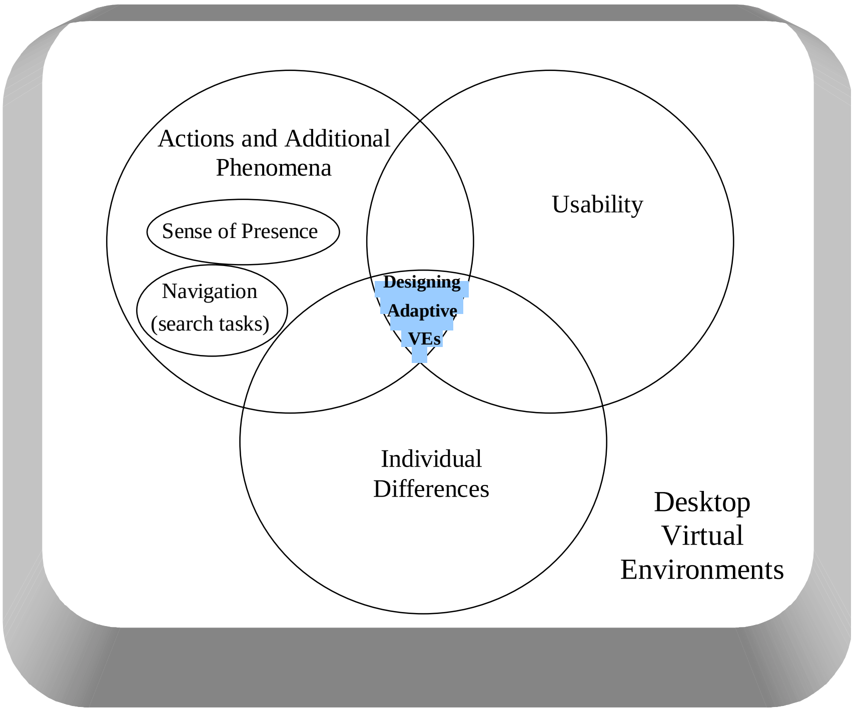

Figure 1.1: Major Research Areas Addressed in this Thesis

1.3 Study Objectives

This thesis focuses on the following aspects which primarily define users' experience within VEs:

- perceived usability of the system;
- user model of acquiring spatial knowledge;
- sense of presence.

These three themes have been addressed through eight study objectives whose interrelationships are represented in Figure 1.2, where *Obj* stands for objective. These objectives are summarised as follows:

1. The investigation of the individual differences related to system usability (Chapter 7).
2. The investigation of the individual differences in navigational patterns followed by users within the VE (Chapters 8 and 9).

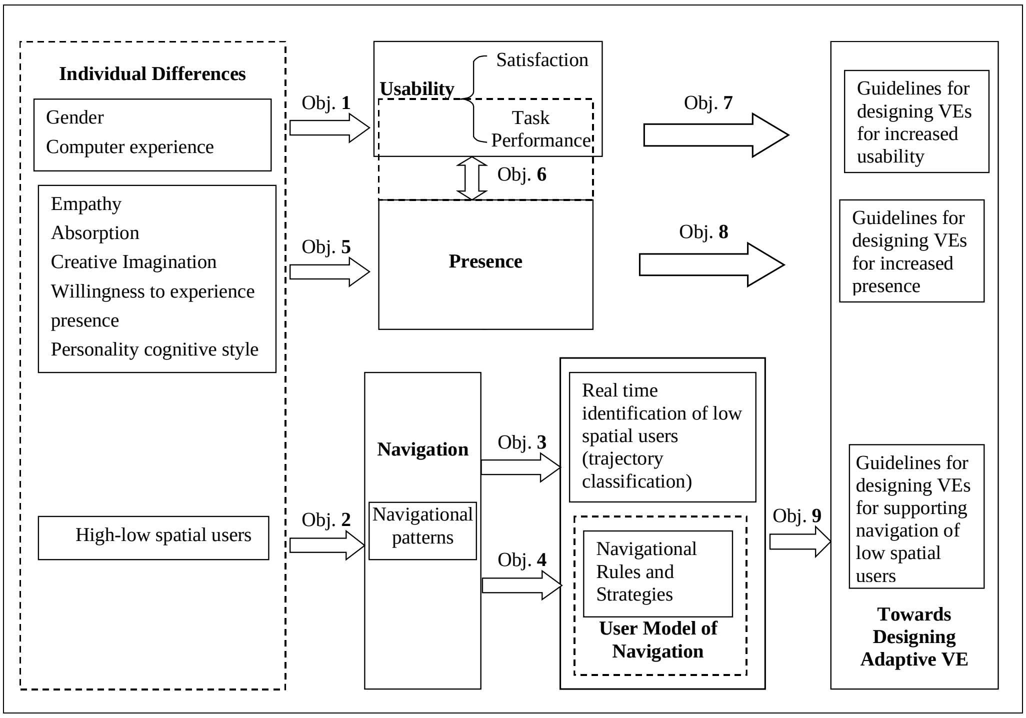

Figure 1.2: Study Objectives

3. The implicit and real-time discrimination of low and high spatial users through on-line trajectory classification (Chapter 8).
4. The investigation of the rules and strategies underlying user spatial behaviour and the development of a user model based on them (Chapters 8, 9 and 11).
5. The investigation of the individual differences which impact on the level of sense of presence (Chapter 10).
6. The investigation of the relationship between presence and task performance (Chapters 7 and 10).
7. The development of a set of guidelines for the design of more usable VEs (Chapter 11).
8. The development of a set of guidelines for the design of VEs able to ensure increased presence (Chapter 11).
9. The development of a set of guidelines for the design of VEs able to provide navigation support to low spatial users (Chapter 11).

1.4 Contributions

The most important contributions of this thesis are:

1. The proposal of a hybrid connectionist-symbolic system for modelling users' search behaviour and understanding users' searching strategies. The non-declarative

knowledge related to searching strategies was investigated by analysing the trajectory paths using methods and techniques developed in the area of machine learning.

2. The proposal of a novel methodology which consists of applying Bézier curves for modelling trajectories. This methodology allows the capturing of navigational rules and can be also employed as a diagnosis tool for discriminating high versus low spatial users.
3. The development of a model of navigation, tailored to naive search tasks.
4. The development of a trajectory classification methodology that allows the online identification of groups of users. It links users' patterns of spatial behaviour and their spatial performance.
5. The empirical investigation of some individual differences impacting on experiencing presence. The impact that a set of factors like empathy, absorption, creative imagination and willingness to be transported within the virtual world, carries on presence has been shown as significant and described through a prediction equation. Few empirical studies have been conducted in the area of users' characteristics impacting on presence, despite the fact that presence literature largely acknowledged their significance.
6. The empirical investigation of the debated relationship between presence and task performance. The implications of these findings are harnessed through suggestions for designing VEs, in order to enable users to experience a higher level of sense of presence.

1.5 Thesis Overview

This thesis is structured along three fundamental aspects related to users' interaction with VEs: usability, navigation and sense of presence. The core idea consists of studying users' individual differences and their impact on each of these aspects.

Chapter two provides an introduction of the concept of usability related to Virtual Reality technologies, highlighting both user characteristics and a taxonomy of tasks that can be performed within VEs. The individual differences impacting on usability of VEs can benefit from the findings of individual difference studies, carried out in the field of Human–Computer Interaction (HCI). The adaptive system are also described together with a brief introduction of user modelling.

Chapter three focuses on those aspects related to navigation within VEs. The concept of spatial models that individuals build while they navigate, and an overview of several navigational models are presented. The individual differences in navigation and possible ways to accommodate them are also described.

Chapter four introduces the concept of sense of presence together with an overview of the most important presence theories. The difficulties related to measuring presence and a summary of instruments and techniques employed for measuring it are presented. Presence determinants are highlighted and the relationship between presence and task performance is discussed.

Chapter five presents the study methodology in terms of sample, apparatus, procedure and measuring instruments. The latter aspect refers to a set of questionnaires, partly designed by the author of this thesis, for measuring user satisfaction and user sense of presence. Other questionnaires have been developed in the area of hypnosis and previous studies indicate their validity and reliability. Another questionnaire measures personality cognitive style.

Chapter six details various machine learning techniques utilised throughout the thesis. These include Self-Organising Maps, Learning Vector Quantisation, Decision Tree, Rule Induction and Recurrent Neural Networks (RNNs). In particular, issues arising from the use of previously mentioned techniques to implicitly capture the knowledge of navigational strategies embedded in user mental model of navigation are described. This chapter also introduces the concept of Intelligent Agents which describes an important application area for designing adaptive systems.

The following five chapters are concerned with the presentation of study results and design guidelines for developing adaptive VEs.

Chapter seven refers to the individual differences related to usability. Two aspects are relevant in this context, namely task performance and user satisfaction. The individual differences impacting on these two aspects have been identified as:

- demographic factors: gender and prior computer experience;
- personality and cognitive factors.

Chapter eight describes individual differences related to navigational patterns analysed from a machine learning perspective. This chapter focuses on two relevant aspects: trajectory classification which offers a basis for discriminating on-line low skilled spatial users from high skilled spatial users, and trajectory prediction. The latter aspect offers a twofold benefit. It enables the exploration of regularities implicitly embedded in the trajectory paths and, their extraction in the shape of symbolic rules governing the spatial behaviour.

Chapter nine presents another method of analysing and discriminating trajectory paths followed by high versus low spatial users, through an attempt to approximate these trajectories with high order Bézier curves. The findings and benefits of this approach as a diagnostic tool for capturing navigational rules of both inefficient and efficient navigators are discussed.

Chapter ten presents the findings related to individual differences in experiencing presence. Each of the following factors: empathy, absorption, creative imagination and willingness to be transported in the VE, and their impact on presence is discussed. Their overall impact is described through a regression equation. The relationship between presence and task performance is analysed in the light of personality cognitive style.

Chapter eleven offers a discussion of study results and proposes a series of guidelines for designing VEs able to accommodate the identified individual differences. This chapter offers also a summary of the navigational rules, based on which a user model of navigation has been elaborated. Finally, it describes the architecture of an agent-based VE — an adaptive version of the ECHOES system.

Chapter twelve provides a review of the main outcomes of this thesis. Future work which might be relevant in this context is also discussed.

The road map (Figure 1.3) is intended to assist the reader by providing navigational clues for better wayfinding in the abstract space of this thesis. It is presented at the beginning of each of the following chapters offering additional orientation support, through indicating the reader's location in the thesis content.

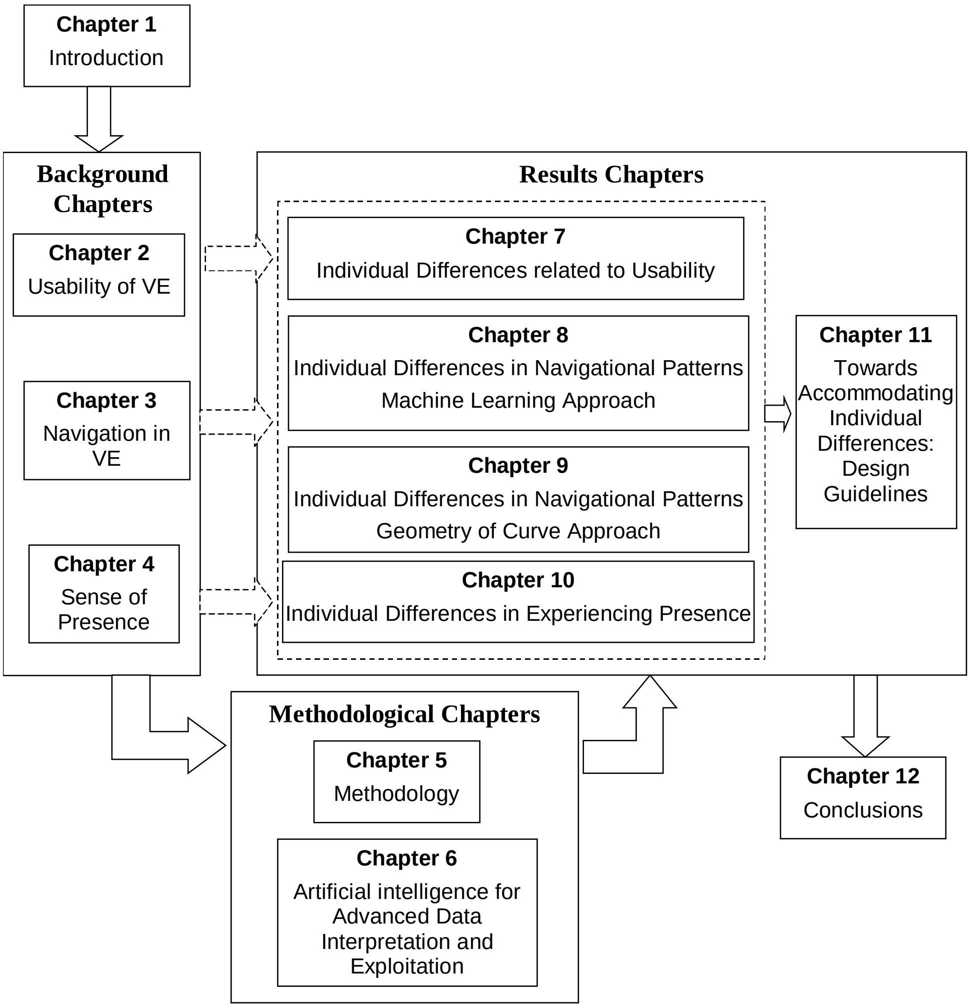

Figure 1.3: Road Map of the Thesis

Chapter 2

Usability of Virtual Reality Systems

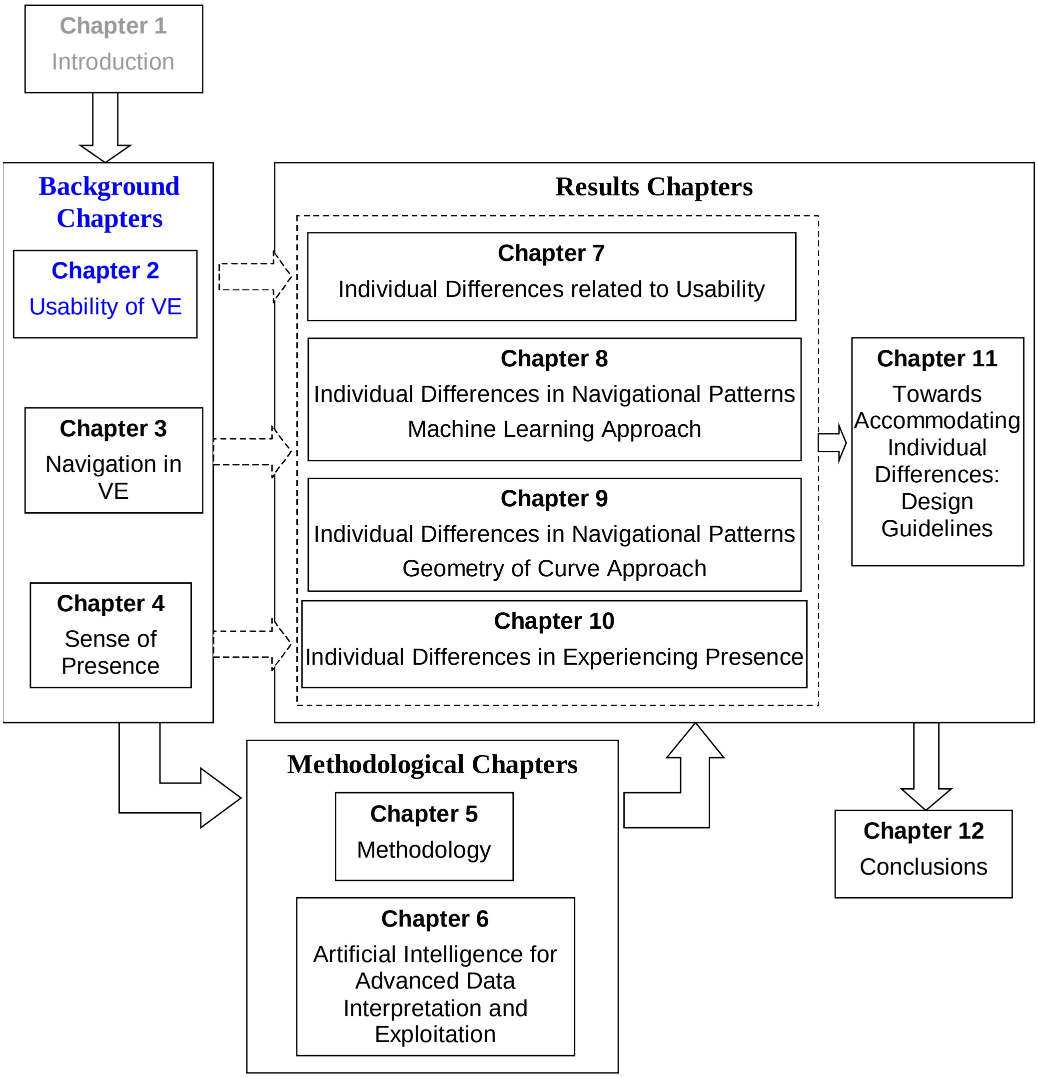

Figure 2.1: Road Map

2.1 Introduction

It has been observed that today, the simple delivery of any kind of artefacts for end user's consumption is not enough to ensure satisfaction and successful exploitation of all the designed features that these products hold. Above all, usability is a business phenomenon and this gives some urgency to all usability related issues (Rubin, 1994). Economic reasons justify the efforts put in both academic and industrial research focusing on system usability. The outcomes of this line of study are expected to lead to higher task performance and increased user satisfaction. Usability is therefore a product quality factor that has grown in importance during the last years.

This chapter introduces two constructs underpinning the present thesis and tries to highlight their interrelationship. It starts by depicting the conceptual delimitations of usability, its goals and its measurements. VEs are then introduced as one of the application areas in Computer Science, which seems to receive relatively little consideration when it comes to usability issues. VEs offer considerable potential limited only by the infancy of the concepts and the technology underlying them. This makes VEs more difficult to design, implement and use than any other conventional interfaces. The next section describes VEs and their features, with an emphasis on task characteristics and user characteristics as major aspects impacting on system usability. Particular attention has been given to navigational tasks in VEs and the difficulty associated with their completion. To meet the need for providing navigational support and accordingly to increase the usability of VEs, adaptive VEs are proposed and discussed.

2.2 Usability

Usability is an umbrella term and the research literature acknowledges both the multidimensionality and the multifaceted nature of this construct. Usability has been considered a research and design discipline, a set of product qualities, an objective and subjective criterion of interaction. Keinonen (1998) defines usability as "relationship between an artefact and a human being who is engaged in interaction with the artefact to achieve some practical goals".

2.2.1 Usability Construct

Originally, usability was related to making systems easy to use and easy to learn, as well as supporting users during their interaction with the equipment. A more operational definition is provided by the international standards related to usability (ISO, 1997), which described usability along the following conceptual dimensions:

- *Effectiveness*: "the accuracy and completeness with which specified users can achieve specified goals in particular environments";
- *Efficiency*: "the resources expended in relation to the accuracy and completeness with which the users achieve goals";

- *Satisfaction*: "the comfort and acceptability of the work system to its users and other people affected by its use".

Following the line of operational definitions, Booth (1989) considered the next four factors as capturing the essence of usability: usefulness, effectiveness, learnability (ease of learning) and attitude (likability). Nielsen (1993) considered the following five aspects as relevant usability attributes: learnability, efficiency (high productivity), memorability (ease of remembering how to use), errors (reduced error rate and easy recovery from them) and satisfaction. In a similar vein, Preece et al. (2002) suggested that usability can be broken down into the following goals: effectiveness, efficiency, safety, utility, learnability and memorability.

An analysis of these sets of factors defining usability led to two dimensions of this construct. One refers to the performance in accomplishing the tasks, while the other one taps a more subjective perception of the interaction with the system. In direct relation to these aspects, two methods of measuring usability have been developed.

2.2.2 Measuring Usability

The modalities of measuring usability can be broadly grouped into two classes: objective and subjective methods (Nielsen, 2000). Objective methods focus on performance measurement expressed in terms of users' behaviour in accomplishing tasks. Subjective methods consist of users' attitude measurement regarding their interaction with the system.

Task Performance

In a broad sense, task performance is a construct related to the notion of ability. In an operational definition, task performance refers to how well the users perform and complete a specific task. This involves a set of criteria for assessing the task completion. Some of the most frequently cited objective measures of task performance (Hix and Hartson, 1993) are:

- task completion time,
- task error rate, and
- task learning time.

User Satisfaction

Typically, user satisfaction or subjective measurement of system usability consists of users' attitude measurement regarding their interaction with the system. User satisfaction is usually measured through self-rating questionnaires administered after the task has been completed and the user's interaction with the system ended (Chin et al., 1988; Kirakowski and Corbett, 1990).

An entire field of research has emerged in order to provide both theoretical background and techniques for producing usable products and systems. Human–Computer Interaction (HCI) focuses primarily on software and hardware usability (Avouris, 2001; Hix and Hartson, 1993; Isensee and Vredenburg, 2000), web usability (Fleming, 1998; Nielsen, 1993), and on specific domains such as hypermedia (Brusilovsky and Maybury, 2002) and virtual reality applications (Gabbard and Hix, 1997). While a great deal of usability research has focused on improving web design and the assessment of different software products, usability studies in the arena of non-immersive VEs have been rather limited (Gabbard and Hix, 1997; Marsh and Wright, 1999; Munro et al., 1999b; Neale and Caroll, 1999).

Before presenting the usability aspects relating to VEs, a basic introduction to the most relevant concepts is depicted. The following section introduces VEs and the most important aspects relating to them.

2.3 Virtual Environments

Virtual Reality (VR), also called Artificial Reality, Cyberspace or Synthetic Environment is an umbrella term, whose meaning has been enriched from computer-mediated systems to technologies, or even to imaginary spaces generated by human fantasy.

Emphasising its main functionality, Aukstakalnis and Blatner (1992) defined VR as "a way for humans to visualize, manipulate and interact with computers and extremely complex data". VR technology offers the basis for the designing and developing Virtual Environments (VEs). VEs are three-dimensional (3D), computer-generated, simulated environments that are rendered in real time according to the behaviour of the user (Loeffler and Anderson, 1994).

The potential of VR can be envisaged, judging by the variety of VEs which have been already developed. A brief description of the most important and commonly used types of VEs is outlined below.

2.3.1 Types of Virtual Environments

A major distinction among different types of VEs refers to *immersive* and *non-immersive* VEs. While immersive VEs involve the restriction of users' senses in terms of their reference to the real world, non-immersive VEs, or desktop VEs, do not restrict users' senses in any way (Fernie and Richards, 2002). Desktop VEs allow the user to maintain awareness of the physical reality (Kaur, 1998). While desktop VEs are probably the most common type of VR systems, due primarily to their low cost, immersive VEs seem more appealing because they enable users to completely immerse their personal viewpoint inside the virtual world (Slater and Usoh, 1995). This is usually achieved through the use of Head Mounted Display (HMD) technology (Isdale, 2002).

Other types of VEs refer to *telepresence*, a technology that links remote sensors in the real world with the senses of a human operator (Ravani, 1991). It proves efficient in enabling individuals to act in real but remote world, through the use of robotic arms. It is used particularly in dangerous or difficult to reach conditions, a specific case being in the human body (Sas et al., 2001).

Projected environments involve a physical space onto which the virtual environment is projected, such as a room as in Cave projects (Wloka, 1996) and the Virtual Dome (Hirose, 1996). The *Cave Automatic Virtual Environment* (CAVE) is a surround-screen and projection-based VR system. This type of VE enables multiple users' participation in a space of the size of a room. Projectors are used to throw full-colour, computer-generated images onto three walls and the floor, images that are viewed with stereo glasses. The high-resolution 3D video and audio inputs facilitate the illusion of immersion.

Mixed Reality (MR), term coined by Milgram et al. (1994), represents a spectrum that extends from real to virtual experiences, with *Augmented Reality* (AR) and *Augmented Virtuality* (AV) bridging the two. MR consists of a combination of telepresence with VR systems, where the computer generated world is merged with the input provided by telepresence, thus enriching the user's perception and experience of the real world (Isdale, 2002; Duffy et al., 2003). This technology allows the digital world to be extended into the user's physical world.

When a user's view of the world is supplemented with computer-generated information which can potentially enrich the meaning of the real world, an AR emerges (Adam, 1993; Balcisoy et al., 2000). The augmentation or enhancement may consist of virtual artefacts placed into the physical world or a display of information about real objects. Enabling users to perform tasks which involve real objects, while receiving additional information about those objects represents a major benefit of AR. The goal of AR is to improve the understanding of the real world by the user.

AV systems are mostly synthetic with some real world imagery added such as texture mapping video onto virtual objects (Milgram et al., 1994). The user is immersed in a virtual world based on real data that is updated in real time. The goal of AV is to present a part of the real world in a simplified environment. The relationships between these types of VEs are better understood when placed on the reality-virtuality continuum (Milgram et al., 1994) (Table 2.1).

	Mixed Reality (MR)				
	↓			↓	
Real Environment	→	Augmented Reality (AR)	Augmented Virtuality (AV)	←	Virtual Environment

Table 2.1: Milgram's Reality–Virtuality Continuum

The main aspect which differentiates MR from immersive VR resides in user's immersion. Within immersive VR systems, which enable user's immersion in an artificial world, users' senses are disconnected from the real world. This aspect prevents them from interacting with real objects. In contrast, MR allows its users to stay in touch and act naturally in the real environment, while their view is overlaid with computer-generated information. There is a different paradigm of user interaction and information visualisation which differentiates immersive VR and MR: while immersive VR systems strive to bring the world into user's computer, the MR systems bring the computer to the user's real work environment (Tryan, 2001).

Collaborative Virtual Environments (CVEs) are multi-user virtual environments, designed to support collaborative activities (Tromp, 1997; Benford et al., 1996; Benford and Fahlén, 1993; Benford et al., 1994). Either immersive or nonimmersive, CVEs provide a potentially infinite, graphically realised digital landscape which offers a framework for users to interact not only with each other but also with different data representations (Churchill and Snowdon, 1998). Several such CVEs have been developed, for example the DIVE system (Benford and Fahlén, 1993) or the MASSIVE system (Greenhalgh and Benford, 1995).

Central to these types of VEs is the idea of multiple users sharing the virtual world. This provides an increased social significance for virtual space as a practical resource, with the purpose of supporting different types of social activities and abilities (Benford et al., 1994).

Benford and Fahln's (1993) spatial model aims to harness the properties of virtual space for mediating social interaction. It proposes five concepts such as medium, aura, awareness, focus, nimbus and adapters. Interactions between people occur through some medium, where some adapters can be used to alter different subspaces such as individuals' aura, focus or nimbus which impact on people's level of awareness of the space, of themselves or of others.

A type of navigation particularly supported within CVEs is *social navigation*, which involves relying on information from other inhabitants of the collaborative world, to help make decisions (Munro et al., 1999a; Dieberger et al., 2000). Apart from the similarities shared with solitary navigation performed in non-collaborative VEs, social navigation is characterised by a series of features which pinpoint its distinctiveness. It requires awareness of the others, communication between participants, negotiating goals, synchronising actions etc. Given these dissimilarities in relation to non-social navigation, investigating social navigation is beyond the purpose of this thesis.

Without being exhaustive, the above description summarises briefly the most important types of VEs and their distinctive features. In order to refer to usability of VEs, the functionality they address and the set of tasks they enable have to be understood.

2.3.2 User's Actions within Virtual Environments

The VR paradigm allows the observer to act in computer generated worlds and the basic goal of VEs is to create a place for people to act (Tromp, 1997). However, due to VEs' specificity, the user's set of actions in them is restricted (Stanney, 1995). Gabbard and Hix (1997) provided a taxonomy of user's actions within VEs, which is based on the one developed by Esposito (1996):

- navigation and locomotion;
- object selection;
- manipulation, modification and query.

This thesis focuses particularly on navigation and associated spatial tasks in a desktop VE. Therefore, this class of user's actions will be briefly introduced in the following subsection. However, given the relevance of navigation topic to this thesis, an entire subsequent Chapter 3 will provide a more thorough description of it.

Navigation and locomotion

Despite the extensive literature about spatial behaviour and its determinants in animals, the experimental work in humans is only fragmentary (Nadel et al., 1998). Some of the reasons for this lack of research and the potential of VEs for covering the existing gap in investigating human navigation are outlined below. VEs are able to provide new methodological possibilities to investigate spatial cognition (Wartenberg et al., 1998; Waller, 2000; Darken and Sibert, 1996a,b; Satalich, 1995). The distinctive features of VEs which transform them in excellent test beds for such studies are outlined below.

One of the main difficulties of investigating human spatial behaviour has been related to its cost along two fundamental dimensions: time and space. Natural experiments identified problems related to recording user's behaviour, while a more controlled environment presents difficulties related to the organisation of the spatial layout and landmark configuration. In addition, each experiment involving locomotion always requires user's investment in terms of physical resources.

VEs are able to partly overcome these limitations of classical studies on spatial cognition because of their characteristic of high controllability of computer graphics stimuli (Mallot et al., 1998). Each natural behaviour, and in particular spatial navigation, is embedded in the perception–action cycle, which justifies the use of VR as a technique for carrying out complex behavioural experiments in well controlled conditions (Mallot et al., 2002). VEs can be built to represent any kind of physical space, from indoor cluttered spaces to large spaces, from urban environments to natural settings, for example those representing terrain, forest, desert, sea or others types of landscapes. VEs can also provide a mere replication of a physical space or a completely new, imagined space. The former provides a perfect setting for testing the transfer of knowledge and skills from VEs to their physical counterparts. In other words, VEs offer the context for training and exploration, enabling the replacement of training and exploration within the physical world. Such a potential is particularly appealing when experiencing the real world is expensive or dangerous, or the environment is difficult to reach or must be known before the interaction (Darken, 1995). VEs present the additional advantage of allowing for time compression (Darken and Banker, 1998).

This thesis focuses primarily on investigating spatial cognition in VEs. Only in rare situations could the experience mediated by VR technology become a goal in itself (i.e. in game industry or arts), whereas usually its ultimate purpose is to serve a better adaptation to the real world. In this case, the possible transfer of knowledge form virtual to real world is of particular interest. Several studies carried out at the U.S. Army Research Institute for Behavioral and Social Sciences led to findings indicating that significant spatial learning occurred as a result of training in a VE (Boswell, 2001). Witmer, Bailey and Knerr's (1995) study suggested that the likelihood of transferring the spatial skills acquired in VE to physical world increases when the VE is designed so as to represent adequately the significant landmarks. Other studies indicate that VEs better support users in acquiring landmark and route knowledge than studying map alone does (Bliss et al., 1997; Goerger et al., 1998). Evidences of significant similarities in the acquisition of spatial knowledge from real and VEs have been identified (Jacobs et al., 1998). For a more detailed review see Chapter 3.

In addition, once a VE has been created, it can always be transformed, at low cost, in order to test additional hypotheses. This suggests another strength of VEs, related to their potential to help experimenters to manipulate particular variables (e.g., field of view, combining different navigation modes etc.), that are difficult or almost impossible to manipulate in physical world. A good control of extraneous variables is also more easily achieved than in the real world. Furthermore, VEs can be designed either to realistically simulate or alternatively defy the laws of physics (Slater and Usoh, 1993a). Along the realism continuum, the potential of VEs for hypothesis testing varies accordingly. An additional purpose, related primarily to the VEs developed for training spatial skills, addresses the users' ability to both learn and represent the spatial characteristics of such virtual spaces (Waller, 2000).

One of the main advantages of VEs consists of their powerful tractable characteristic (Amant and Riedl, 2001), which enables accurate spatio-temporal recording of users' trajectory within the virtual space. Such recording is carried out in real time, automatically and unobtrusively (Mallot et al., 1998).

To conclude, VEs are suitable technologies to be harnessed for studying and training spatial behaviour, given their characteristics, summarised by Durlach (2000) as follows:

- scaling space and time;
- emphasising components of interest;
- tracing user behaviour;
- real time adaptation;
- realistic or unrealistic features for the purpose of training.

All these strengths of VEs, however, come at a price. As Sayers (2000) observed, navigation in particular has been found to be central to the usability of interfaces to VEs on desktop systems. Factors that may contribute to the difficulties encountered during navigation in VEs are related to a general lack of familiarity with using VEs, and in particular to people's lack of knowledge of their position, their orientation and the structure of a VE (Ruddle et al., 1998). Other difficulties arise because of the sensory deprivation: among the five senses, VEs in general, and desktop VEs in particular privilege vision. There may be limitations in interactions, such as the absence of tactile feedback, substitutions, such as the use of gestures for navigation instead of whole body movement, or empowerments, such as the ability to walk through walls (Kaur, 1998). Desktop VEs, even in 3D versions, present limitations with respect to depth perception. Another serious threat to the usability of VEs is related to motion sickness or cybersickness (Stanney et al., 1998a).

The potential of VEs for studying navigation and the limitations of VEs particularly associated with navigation are two intertwined aspects which require the need of studying the usability of VEs for supporting navigation. A promising direction of research in this sense, which is also followed within this thesis, consists of exploring the possibilities of designing adaptive VEs able to support navigation (see Chapter 11).

Conceptual delimitations The etymology of navigation refers to "driving a ship" *agere* — to drive and *navis* — ship. This understanding reveals that navigation is more than travel and it requires technical skills, knowledge and a plan.

Montello (2003) defined navigation as "coordinated and goal-directed body movement through the environment", and identified two components of this construct:

- locomotion, which is the body movement through the environment, coordinated to local surrounds; and
- wayfinding, which is efficient goal-directed planning and decision-making plan of navigation, coordinated to distal environment.

Darken and Sibert (1996b) present a classification for wayfinding tasks:

- Naive search, searching tasks where users have no prior knowledge of target location;
- Primed search, searching tasks where users know location of target a priori;
- Exploration, wayfinding tasks where there are no targets.

Given the complexity and goal-dependent characteristic of human wayfinding behaviour it is difficult to identify a particular cognitive process underlying wayfinding in general, apart from specific processes such as path integration, route retrace or landmark recognition (Golledge, 1999). This difficulty is even more increased when the individuals exhibiting navigational strategies are completely unaware of using them (Golledge, 1996).

Search Strategies Because of the relevance of search behaviour in the context of this thesis, this section presents a review of the most common *search strategies* which have been identified in the real world.

Strategies for maintaining orientation during locomotion focus on updating knowledge about location. Two such strategies are landmark-based updating and dead-reckoning. Landmark-based processes emphasise the role of landmarks whose recognition keys the current physical location to its counterpart on the cognitive map, supporting wayfinding. The dead-reckoning process consists of keeping track of both direction of movement and distance covered, by paying attention to turns performed and speed/acceleration at which one moves (Montello, 2003; Rodrigo, 2002).

Montello (2003) summarised several other strategies employed for maintaining orientation, such as verbalising the landmarks, memorising the number and order of turns along a route, reaching a high point of maximum visibility, look-back strategy, or edge following, a strategy inspired by maritime navigation. When one experiences disorientation, recommended strategies are retracing steps or route sampling, which consists of covering short distances from the current location in as many directions as possible while performing dead-reckoning at the same time.

Darken and Sibert (1996a) investigated the impact of different navigational assistants such as map, grid, and map and grid on spatial task performance. A qualitative analysis of the verbal protocols and video recordings led to the identification of four basic search strategies: edge, lawnmower, area, and heuristic. The edge following techniques, particularly employed by the control group exposed to the most difficult VE, consists of searches of the boundaries of the large masses for targets. While it is time efficient, this search strategy may induce disorientation, since the participants did not maintain an exocentric frame of reference. One way to overcome such disorientation led to a lawnmower strategy, through which the user constructs an absolute reference for reorientation. Once the user finds a corner he/she searches up and back in long parallel strips, in a pattern movement similar to a lawnmower. The area strategy consists of dividing the space into small parts, which can serve both as landmarks for path following and for orientation. The heuristic strategy consists of searching for the places considered most likely to contain a target. Once these places are identified, they are circled.

The findings of this exploratory study suggest that the identified search strategies are dependent on the navigational cues. Unfortunately the authors did not provide any numerical data with respect to the frequency of this strategies nor their correlation with performance on spatial tasks, which could have offered a basis for assessing the quality of strategies. Their study exhibits other limitations in terms of the reduced sample size and the knowledge elicitation techniques. Given the implicit nature of spatial strategies, the difficulties of accessing them cannot be overcome only through the analysis of verbal protocols.

Despite the limited range of actions enabled by them, VEs have been found potentially suitable for a large and diverse set of applications. The development of VR technologies appealed to different fields and several application areas have emerged in the last decade. Gabbard and Hix (1997) identified the most common current areas where VEs have been successfully employed, such as: medical and military training and simulation, entertainment, decision support, scientific visualisation, engineering and architectural design, teaching and education manufacturing. Such areas of application harnessed the potential of each type of action enabled within VEs.

Narrowing our focus down to spatial tasks, VEs prove again their versatility by the various fields of research they can support. Durlach (2000) summarised four of such fields of research that involve spatial behaviour:

- VEs as research tool to help advance fundamental understanding of spatial behaviour (exploring space, searching for items, planning/following a route, constructing maps etc.) (Waller, 2000; Montello, 2003);
- VEs used to help assess spatial abilities and skills (Waller, 2000; Darken and Sibert, 1996a);
- VEs used for development and evaluation of methods for improving spatial behaviour in VEs. This direction of research addresses in particular the difficulties encountered by users while navigating in VEs (Darken and Sibert, 1996a; Waller and Miller, 1998);
- VEs have been used for the purpose of improving spatial behaviour in the real world (Satalich, 1995; Darken and Banker, 1998; Bliss et al., 1997; Dijk et al., 2003).

Given the significance of navigation for VEs, it is imperative to increase the usability of VEs in terms of making them easy to navigate. This would free the user's cognitive resources, making them available for the processing of any concurrent tasks (Vinson, 1999). Despite the apparent versatility which VEs seem to exhibit, Gabbard and Hix (1997) raised an interesting issue about their suitability. They proposed a more cautious attitude, such as the one involving a thorough examination of the usability of VEs for each given set of tasks, in the contexts of each application area.

2.4 Usability of Virtual Environments

Usability evaluation of VEs has received limited attention from VE designers. However, this does not imply a lack of awareness of the necessity of carrying out such studies, but is related to the difficulties encountered in this endeavour. One of the main problems to overcome in this direction consists of developing techniques needed to perform efficient usability evaluation (Gabbard et al., 1999). Therefore "techniques and tools for interacting with virtual environments are at the core of research and development efforts around the world" (Singh and Feiner, 1995). In a similar vein, Gabbard and Hix (1997) noted:

> While VEs have been gaining broad attention, usability of the user interface has become a major focus of interactive system development. Yet despite

> intense and widespread research and development in both VEs and usability, the exciting new technology of VEs has not yet been closely coupled with the important characteristic of usability — a necessary coupling if VEs are to reach their full potential.

The difficulties encountered in developing such evaluation techniques are related to the relatively novel virtual reality technology which continues to challenge VE developers with problematic technical and software issues. The attempts to address such issues are resource consuming and therefore impede both a more user-centred approach to design (see Section 2.5.1) and the availability for performing usability evaluation (Gabbard et al., 1999).

One of the main problems relating to limited usability evaluations of VEs is the lack of feedback for improving their design. There is little understanding about how VEs are being designed and even less guidance about how design should be done (Kaur, 1998).

Concerns regarding usability evaluation of VEs are rooted in the observations that users' interactions with VEs suffer from frequent difficulties, which lead to low system usability (Miller, 1994). Kaur (1998) identified as common problems encountered in VEs disorientation, perceptual misjudgements and confusion with unnatural interactions. The author proposed as a potential cause of these difficulties the interaction between user and VE, VE which apparently mimics the interaction with real world, but in fact has its own idiosyncrasies. Once these limitations are understood, they could be overcome in two complementary ways. On the one hand, the user needs to be able to adapt and tolerate limitations, to understand and adapt to substitutions and take advantage of empowerments (Kaur, 1998). On the other hand, the VE itself can be modified in order to support better user needs. The adaptive VEs are such attempts and are presented in Section 2.6.

Both these directions emphasise the important role played by human factors or user's characteristics in designing VEs (Kaur, 1998; Macredie, 1995; Rushton and Wann, 1993) since the final purpose of any system is to serve the end user, instead of making use of a specific technology or being an elegant piece of code (Norman, 1986). The most intuitive way to address this final purpose is through some theoretical and empirical studies of users interacting with the system. Given the array of interests, skills, experience, cognitive abilities and personalities traits characterising these users, such studies should focus primarily on users' individual differences and how these impact on the aspect of interest. The next section introduces the individual differences relating to usability of VEs, whose accommodation is a major goal of the adaptive systems.

2.5 Individual Differences Related to Usability

The increasingly widespread use of VR technology has highlighted the need for a better understanding of a number of fundamental issues concerning human factors in a VE. Despite the availability of a large range of user interfaces, there is an inherent limitation related to their usability, since they are designed with only a generic, ideal user in mind

(Chen, 2000). This consequently influences the subjective perception of satisfaction experienced by users during their interaction with the system.

As Gabbard and Hix (1997) pointed out, the research in the area of VR can benefit from the findings of individual differences studies carried out in the field of HCI. They identified the following user characteristics which lead to individual differences on the perceived system usability: user experience, technical aptitudes, gender, and age.

Each of the previously mentioned characteristics will be further detailed. An observation should be made at this point. There are three key concepts related to any learning process: knowledge, skills and attitudes (Bloom, 1956). They shape user experience when the user is interacting with a given set of tasks.

Knowledge refers to specific information, such as principles, concepts, and generalisations necessary for problem solving. Identifying the type and complexity of users' knowledge helps in understanding how to design the tasks and the context (i.e. VEs), in order to compensate or challenge the users.

Skill is defined as the ability to bring about some end result with maximum certainty and minimum expenditure of time and energy (Guthrie, 1952). Attitudes involved in the learning process refer to the user's intrinsic motivation for learning while performing the tasks, together with the willingness to approach them, expressed in terms of interest or positive feelings.

User prior experience with a specific type of task leads to the acquisition and training of a set of skills required by the task and impacting on its completion. The direct benefit of this is increased performance for particular types of tasks. However, the improved performance is not restricted only to these types of tasks, but can extend to others, as long as there is a core of shared components between the two set of tasks. In this case, one can talk about a *positive transfer* enabled by the user's ability to recognise similarities between the two sets of tasks (Egan, 1988). Traditional computer experience, and in particular previous exposure to VEs usually enables users to perform better (Waller et al., 2001).

Due to the prevalence of navigational tasks within VEs, a particular set of technical aptitudes, such as spatial orientation, spatial memory, and spatial visualisation impact significantly on both task performance and user satisfaction (Egan, 1988). The three-dimensionality feature characterising most of VEs puts additional demands on low spatial users and therefore impedes their performance (Waller, 2000). Identifying modalities to address the limitations experienced by low spatial users has been an area particularly encouraged and therefore receiving increasing attention among VEs designers (Gabbard and Hix, 1997; Stanney, 1995).

Age and gender are user characteristics often mentioned as impacting on task performance and experienced level of satisfaction, particularly in the context of spatial tasks (Lawton, 1994; Waller, 2000).

Given the large diversity of users exposed to ever-increasing technologies of any kind, the issue of usability has significantly grown in importance. Acknowledging the impact of individual differences on perceived system usability, a new design approach has emerged within the field of usability research.

2.5.1 User-Centred Design

User-centred design (UCD) is a recent term, coined to describe an approach that has been around for decades. “It represents not only the techniques, processes, methods, and procedure for designing usable products and systems, but just as important, the philosophy that places the user at the centre of the process” (Rubin, 1994). User-centred design essentially means that products are designed according to users’ information needs and expectations and comprises a variety of techniques, methods, and practices (Rubin, 1994), outlined below.

- *Participatory design* assumes the involvement of some representative users in the design team. This approach places the end user into the heart of the design process from its beginning, enabling a direct access to user’s knowledge, skill set, and attitudes along the design process.
- *Focus group research* involves a sample of representative users invited to evaluate preliminary concepts, at an early stage of their design. The high potential of focus group resides in the simultaneous participation of all the users involved in the evaluation. This ensures an in-depth exploration of users’ judgments and feelings about those concepts. Valuable ideas about how acceptable those concepts are, or how they can become more acceptable are an important outcome of a focus group.
- *Surveys* are used to extract information about a potential or an existing product, through the employment of larger and representative sample, which enables the generalisation of results to user population.
- *Design walk-through* aims to reveal the potential user mental model through an early concept of a product. Through a role playing, this approach involves one of the member of designing team to carry out, under guiding, the actual tasks. Once recorded, the difficulties encountered are addressed later.
- *Paper and pencil evaluations* consist of a set of questions for assessing one or several attributes of the product. The questions are administered to users in paper format. The main advantage of this technique consists of reduced cost and high speed of collecting information.
- *Expert/Heuristic evaluation* involves a review of the product by a usability specialist.
- *Usability testing* employs techniques to collect empirical data while observing users using the product to perform representative tasks.
- *Field studies* is a review of a product placed in a natural setting, where customers receive some compensation for helping in evaluating the product. Data, such as

patterns of use, difficulties and user attitudes, are collected and used to refine the product.

- *Follow-up studies* are similar to the field studies, although they occur after formal release of the product, with the purpose to collect data for the next release. They provide more accurate assessments of usability, since the actual users and product are encompassed holistically in natural settings.

The main goal of studying individual differences and their implications resides in proposing new effective ways to accommodate them in user-centred design process for increasing both task performance and satisfaction associated with the resulting product. As Benyon (1993) noted, "one solution to the problem of usability ... is to supply the system with a suitable theory of interaction and how interaction can be improved". One way to address the individual differences is through user adaptive systems, because "in an increasingly accommodating world, VEs should be able to adapt to both physically and mentally challenged users" (Gabbard and Hix, 1997).

2.6 Adaptive Virtual Environments

Despite their increasing appeal, adaptive systems in general and adaptive VEs in particular pose several challenging problems to their designers. Tracking user behaviours, analysing and extracting relevant behavioural patterns, identifying the interrelationships between these patterns which should become part of a model aimed to explain and predict user behaviour represent aspects which require a great deal of work. Once the user model has been identified, one should search for possible ways to address the most important aspects embedded in this model which can potentially increase task performance. The real time constraints for providing adaptivity, and the additional difficulties of predicting the dynamics of user behaviour are aspects which depict the problem domain of building such adaptive systems.

2.6.1 User Adaptive Systems

Jameson (2003, p. 317) defined user-adaptive system as follows:

> An interactive system that adapts its behaviour to individual users on the basis of processes of user model acquisition and application that involve some form of learning, inference or decision making.

The general schema of a user-adaptive system (Jameson, 2003) is presented in Figure 2.2, where ovals represent input or output, rectangles represent processing methods and the grey 3D figure represents stored information.

Langley (1997) defined adaptive user interface as "an interactive software system that improves its ability to interact with a user based on partial experience with that user". Emphasising the concept of *adaptability* as a feature of systems able to cope with dynamically changing user requirements, Savidis et al. (1997) noted that it reflects a

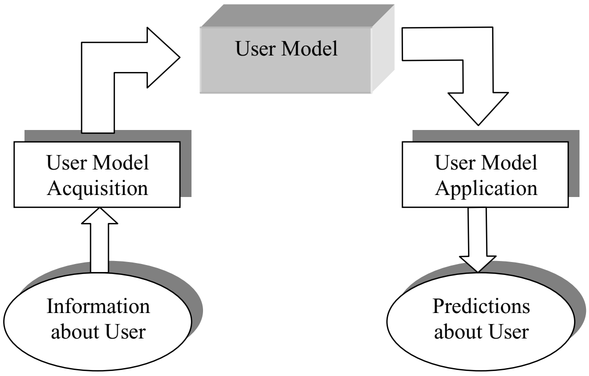

Figure 2.2: General Schema for User Adaptive Systems

"capability to automatically tailor itself initially to each individual end-user". These definitions emphasise two key aspects which distinguish adaptive systems from other intelligent interfaces:

1. The central role of user modelling. This involves acquiring information about the end-user, usually by employing machine learning techniques (see Chapter 6). The main outcome of this stage consists of identifying the users' patterns of behaviour and drawing assumptions about them. As Kobsa (1994) noted, the systems should also be capable of storing these assumptions appropriately and inferring new ones.
2. Tailoring system behaviour to the end-user. This involves comparing current user's behaviour with the model previously acquired and deciding how to adapt the system in order to meet user's perceived needs.

Jameson (2003) identified two major purposes of user adaptive systems in terms of supporting system usability and user modelling. He detailed these two goals by nine functions:

- Supporting system use:
    - taking over parts of routine tasks,
    - adapting the interface,
    - giving advice about system use,
    - controlling a dialog;
- Supporting information acquisition:
    - helping users to find information,
    - tailoring information presentation,
    - recommending products,
    - supporting collaboration,
    - supporting learning.

Adaptive Virtual Environments

VEs feature an appealing potential not only for studying spatial skills and abilities but, more importantly, for training them. The well-known large inter-subject variability characterising these skills raises the issue of their proper assessment. In this respect, VEs have a lot to offer, given their capacity of providing frames for the applied spatial tasks as complementary assessment tools to traditional tests of spatial skills and abilities. An interesting aspect in this context relates to the limited predictive validity of these tests with respect to performances on spatial tasks in VEs. One major reason which explains this refers to the fact that whereas tests seem to focus on spatial properties of objects, the tasks focus holistically on spatial properties of environments (Durlach et al., 2000).

As Durlach et al. (2000) noticed:

> Not only can this technology (VE) be used to provide a wide range of basic spatial skills and abilities training exercises . . . , but it is also capable of providing a complete and real time continuous record of trainee responses and thus provide immediate feedback.

Given both importance and prevalence of navigational tasks within VEs, surprisingly little effort has been invested in the development of adaptive VEs in order to accommodate individual differences which lead to significant difference in user performance. *Navigation assistance* in VEs is a necessity, given the difficulties encountered by low spatial users during their navigation (Benyon, 1993).

To the best of my knowledge, there is only one example of an adaptive virtual environment developed for supporting navigation, at whose core lies a user model of navigation. However, this system is not a VE such as that described in Section 2.3, based on a physical metaphor, but a hypermedia VE or so-called information system. This model led to the identification of two strategies employed during search in abstract spaces, strategies mapping individual differences in the style of processing information (Ford et al., 1995; Ford, 2000; Chen and Ford, 1997). The *holistic* strategy enables a global perspective of the content being learned, aiming to build a broad conceptual overview into which details will fit later, while *serialist* strategy enables a local learning, based on a thorough examination of individual topics with the overall picture emerging later. Such an intelligent adaptive system can identify user's learning strategies, classify these strategies in terms of a learning model, offer individualised learning support, and use the feedback for improving the model over time. A review of other attempts of building adaptive VEs for training navigation is presented in Section 3.3.3.

Given the central role played by user model in user adaptive interface, the following subsection introduces some relevant issues in the area of user modelling. Referring to navigation in information systems, Ford (2000, p. 543) noted:

> Current technology allows the development of information systems that offer flexibility in terms of routes through subject content and a rich set of navigational tools enabling varying levels of user and program control. However,

> we urgently need robust user models to enable us to optimize the deployment of such facilities. Research into individual differences suggests that system efficiency and effectiveness may be enhanced by adapting to individually different needs on the part of users.

2.6.2 User Modelling

User modelling is a growing discipline in the field of HCI, extending itself in various areas which focus on the development of user adaptive systems. The major reason for this resides in the fact that these systems are and will continue to be used by heterogeneous user populations. In order to adapt themselves to the end-user, systems must be able to make assumptions about their users, relevant for tailoring their behaviour to the users (Kobsa, 1994; Fischer, 2001).

The field of user modelling benefits from methods developed in other areas, for example machine learning, knowledge representation, and HCI, adapted to the specific needs of this field (Kobsa, 1994). For a detailed presentation of some of these techniques, see Chapter 6.

"A distinctive feature of an adaptive system is an explicit user model that represents user knowledge, goals, interests and other features that enable the system to distinguish among different users" (Brusilovsky and Maybury, 2002).

A user model is a model that a system has of its users. Such a model resides inside a computational environment, as opposed to the mental model, developed by users with respect to the systems and tasks, and which resides in users' heads (Fischer, 2001; Norman, 1983; Finin, 1989) (see Section 3.2.1). The impact of user mental model on successfully performing tasks with any kind of system raises the need of taking this model into consideration for the purpose of system design. This would ensure increased system usability (Preece, 1993). According to their purpose, user models could be used to describe (Webb et al., 2001)

- the cognitive processes that underlie the user's actions;
- the differences between the user's skills and expert skills;
- the user's behavioural patterns or preferences;
- the user characteristics.

Users often encounter difficulties when navigating in unfamiliar physical places, and in particular in unfamiliar VEs (Vinson, 1999; Waller, 2000; Dijk et al., 2003). The computational complexity characterising VEs imposes limitations on the level of visual details accommodated by virtual worlds (Ruddle et al., 1997). This is expressed in terms of fewer landmarks and depth cues (Vinson, 1999). The problems encountered in VEs are primarily related to limited sensorial stimulations. This applies especially to desktop VEs because of their drawbacks such as restricted view field (Waller et al., 1998), absence of peripheral vision (Ruddle et al., 1997), the difficulties of depth perception, restricted kinaesthetic (Waller et al., 1998) and proprioceptive inputs (Ruddle et al., 1997), and motion sickness as a negative side-effect of navigating in VEs (Harm, 2002). These difficulties of navigating in unfamiliar VEs suggest the need to support navigation in VEs (Vinson, 1999). One way to address this is through accommodating users' individual differences.

2.6.3 Accommodating Individual Differences

Accommodating individual differences in navigation related areas can benefit from the methodology proposed by Egan and Gomez (1985), based on Messick's work (1976) on accommodating individual characteristics for instructional process (Chen et al., 2000). This involves three strategies such as the challenge match, the capitalisation match and the compensatory match.

- *The challenge match* is generated by high task demands which strain users' capabilities and force them to adapt. It works well when user abilities are properly estimated and the challenge is not too high to lead to failure or lack of motivation.
- *The capitalisation match* involves harnessing the user potential, in terms of knowledge and skills, through properly tailored tasks which will not exceed these capabilities.
- *The compensatory match* addresses particularly user's weaknesses and limitations through additional help such as training, assistance or mediators unavailable by default.

For instance, Stanney and Salvendy (1995) stressed the significance of the spatial mental model of navigating in abstract informational spaces, as a key task component that caused the differences between high and low spatial individuals' task performance. By eliminating the need to mentally visualise the structure of the information, low spatial individuals were able to perform as well as high spatial individuals. In this case, the interfaces successfully compensated low spatial users.

The compensatory match has been further developed, through *supplantation* which entails engaging in the activity on behalf of the user so that the required level of competence is reduced, and through *facilitation* which consists of providing tools for enhancing user's engagement in solving the task, i.e. feedback, appraise, validation, review (Ford, 2000).

Investigating possible ways of addressing cognitive style-related individual differences in searching hypermedia, Ford (2000) suggested three access modes to enable differential navigational patterns:

- *Autonomous access*, which enables users to choose access patterns for themselves.
- *Prescribed access*, which requires both a mechanism for assessing the end-user competence and a model robust enough for generating an effective access pattern for each user on the basis of such an assessment.

- *Recommended access*, which offers a default navigational access mode, possibly overridden by the user.

Egan and Gomez (1985) suggested a three stage approach to accommodate individual differences: isolation, assaying, and accommodation. These stages relate to user, to task and to the match between user and task (Chen et al., 2000)

- Isolation consists of identifying those individual differences with maximal impact on task performance.
- Assaying involves the identification of those components of task that account for performance variability.
- Accommodation consists of altering previously identified key task components in order to adapt the task to user capabilities according to one of the three matching strategies.

2.7 Summary

This chapter introduced four concepts relevant to this thesis: usability, VEs, individual differences and adaptivity. It also emphasised the relationships between these concepts in the light of goal of this thesis: designing adaptive VEs through accommodating individual differences in experiencing presence and navigational patterns. The usability of VEs is challenged by both lack of design methodology and technological problems. While a great deal of efforts has been invested in improving VEs for increased usability by manipulating technological aspects, there is a lack of research on human factors whose impact on perceived usability is even higher (see Section 3.3.2).

In light of this, the chapter argues for the suitability of VEs as alternative methodology for investigating aspects related to spatial cognition, and for accommodating individual differences for increased performance of spatial task. The relevant aspects regarding adaptive VEs are briefly outlined, with a particular emphasis on the central role of user modelling. Given the relevance of navigation for this thesis, this theme has been briefly introduced, while the following chapter will be entirely dedicated to it.

Chapter 3

Navigation in Virtual Environments

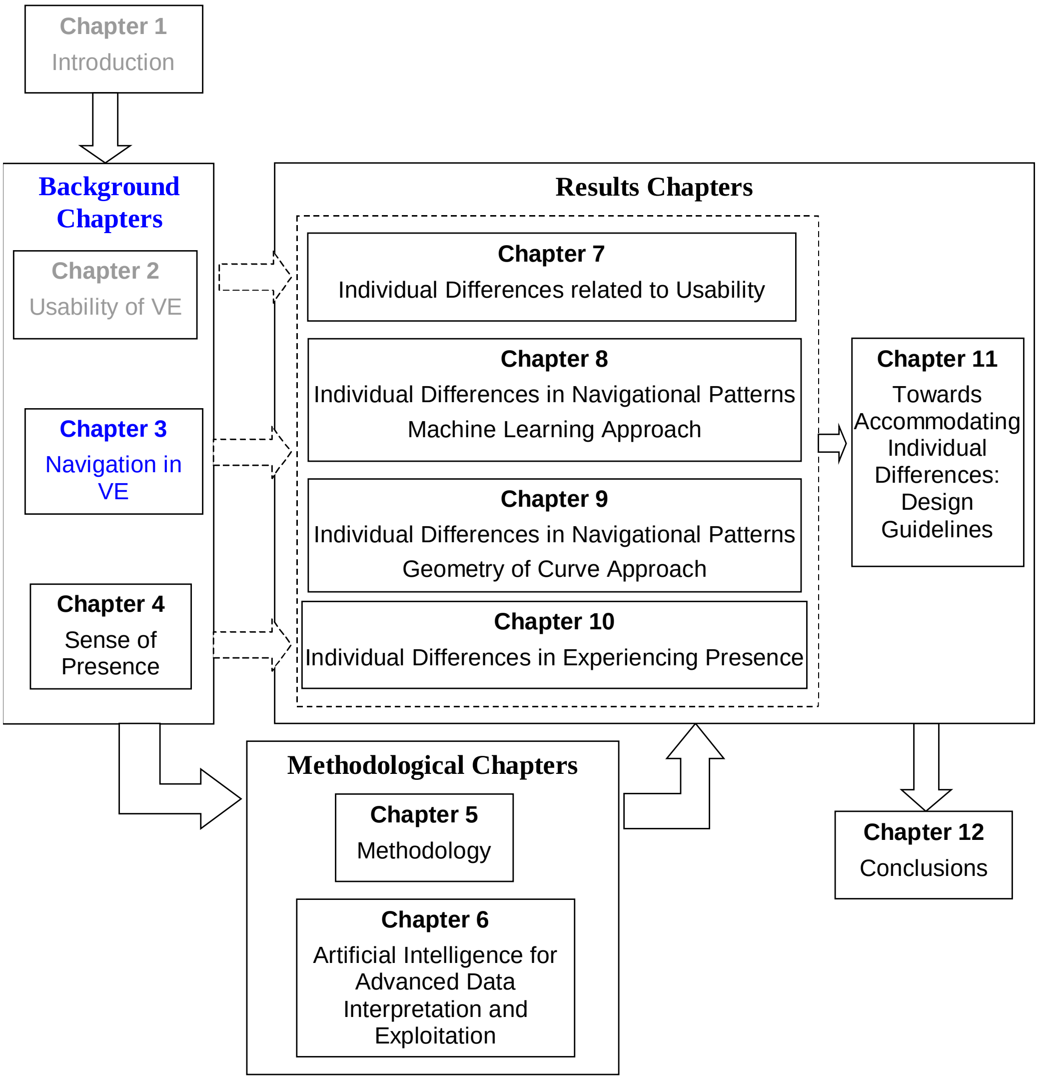

Figure 3.1: Road Map

3.1 Introduction

The need for understanding human spatial behaviour in both real and virtual worlds has been largely acknowledged. This is due to the prevalence and significance of this specific behaviour and to the high psychological distress associated with its failure (i.e., getting lost). The study of spatial behaviour provides both theoretical and practical benefits.

At a theoretical level, the investigation of spatial mental models enriches the understanding of how humans perceive the space, make sense of space and exploit it. The first part of this chapter (Section 3.2) focuses on this aspect. It particularly discusses how humans acquire spatial knowledge and how this knowledge can be elicited by investigators for understanding both the acquisition process and its product, such as cognitive maps.

Spatial mental representations reflect the inherent complexity of human spatial behaviour. Such complexity contributes to the challenges and error-proneness which define spatial behaviour. These difficulties are even larger in the case of navigation in Virtual Environment (VEs) (Waller, 2000) (see Section 2.5). Therefore, the understanding of human spatial behaviour, in both physical and virtual worlds, may have a tremendous practical impact. One way to exploit this understanding is through identifying guidelines to support efficient spatial behaviour. When employed for designing VEs, these guidelines could considerably improve the usability of VEs (see Section 2.6.1).

Most of the studies concerned with the development of adaptive VEs have focused on technological factors and navigational tools applied irrespective of any user model. Thus, this chapter presents also a review of the designing guidelines elaborated for making VEs better places to navigate in. Such guidelines present some limitations which this work tries to address.

The difficulties of investigating spatial mental models and the limitations of techniques developed for this purpose explain the lack of studies in this area. This thesis aims to address this gap, by focusing on investigating user spatial mental model. One of its major contributions is the proposal of machine learning techniques to overcome the limitations of traditional methods for eliciting such models.

This chapter addresses some fundamental aspects of spatial cognition whose basic concepts have already been introduced in Section 2.3. It takes the reader on a journey starting with a review of spatial mental models. The chapter introduces the concept of representations of spatial knowledge together with the associated methods which have been used in externalising and analysing them. A prototypical instantiation of these representations is captured by the construct of *cognitive maps*, whose features are briefly described. In particular, the chapter presents a critical review of both direct and indirect methods employed in eliciting or accessing mental models, and spatial mental models in particular, together with their strengths and limitations. Accessing the spatial representations paves the way towards the understanding of the mental model of navigation. This chapter examines different models of navigation developed in the fields like: experimental psychology, artificial intelligence, robots and neuroscience (Montello, 2003). The reviewed literature lacks systematic work in addressing the rules or strategies describing efficient spatial behaviour. I propose an alternative methodology for eliciting spatial knowledge through stressing the rigour and plausibility of connectionist models aimed to extract those efficient navigational rules and strategies.

After reviewing the theoretical and empirical work focusing on spatial mental models, spatial learning within VEs is considered. Given the prevalence of spatial tasks and their impact on the perceived usability of VEs, the topic of designing better VEs for assisting navigation lies at the core of this thesis. This chapter places this topic in the frame of identifying and accommodating individual differences associated with navigation in VEs.

3.2 Spatial Mental Models

This section briefly introduces the concept of mental models together with the issues pertaining to their acquisition and elicitation. Aiming to provide a basis for the spatial mental models, such a presentation highlights also the difficulties encountered in order to reach and fully describe mental representations in general, and those of spatial learning in particular.

3.2.1 Mental Models

In the broader sense, mental models are constructs which try to explain human understanding of objects and phenomena (Johnson-Laird, 1981; Winn, 2003). In her *Psychology of Mental Models*, Gentner (2002) defines mental model as “a representation of some domain or situation that supports understanding, reasoning, and prediction”. This definition stresses the functions served by mental models. Simplistically, people carry small-scale models in their head which have correspondence to the external environment they represent, for instance, the spatial layout of a real or physical environment (Henderson et al., 2002).

Mental models consist of deeply rooted assumptions, continuously processed for each situation (Henderson et al., 2002) which have been described as representations that users adopt to guide their interactions and aid their understanding of the system (Hanisch, 1991). The representations embedded in mental models are more than mere copies of the external reality: such representations consist of a higher organisation of knowledge with an integrated structure (Winn, 2003). Other characteristics of mental models are summarised below (Gentner, 2002):

- Mental models represent qualitative relations rather than quantitative relations;
- Mental models permit mental simulations;
- Mental models can be contradictory, in the sense that people can hold two inconsistent models within the same domain;

- Mental models held by novices usually are context-specific and lack generalisation.

These characteristics of mental models have been found to facilitate learning, retention of procedures, and the invention of procedures for functioning in an environment (Winn, 2003). A mental model concerned with the interaction between a user and a system involves a set of knowledge and skills about its operations and about the relationships between its components (Kieras and Bovair, 1984).

The difficulties of building an accurate mental model relate to the difficulties associated with the learning process, mainly because it is hard to investigate unconscious learning (Johnson-Laird, 1981). Thus, the analysis of mental models could reveal the learning process. Especially the inaccurate mental models and the errors made by a learner could help understanding how the learning takes place (Gentner, 2002).

Mental models consist of two fundamental types of knowledge, whose elicitation empowers the capacity to understand them and to adjust the system accordingly, to better meet users' expectations and increase the system usability.

The distinction between *procedural knowledge* and *declarative knowledge* has long been acknowledged in many theories of learning and cognition (Anderson, 1976, 1983; Sun and Zhang, 2002; Slusarz and Sun, 2001). It equates to the distinction between explicit and implicit knowledge (Slusarz and Sun, 2001). Declarative knowledge is explicit knowledge that people can report and of which they are consciously aware. Offering a descriptive representation of knowledge, declarative knowledge expresses facts, like what things are (Turban and Aronson, 1998). At the other extreme of a continuum is tacit knowledge, a term coined by Polanyi (1958; 1966) or implicit knowledge, whose core idea resides in the observation that people know more than they can verbalise. The decision rules underlying the performance are hidden from the person exhibiting them. They form part of a *user model* which enables the execution of some tasks because of the technical skills capturing the "knowing-how" (Anderson, 2000). Because of the lack of awareness characterising it, implicit knowledge is usually taken for granted (Ambrosini and Bowman, 2001). However, implicit or procedural knowledge offers a deeper understanding of the environment since they involve declarative knowledge for making inferences about how things work under different circumstances (Turban and Aronson, 1998).

Anderson (1983) proposed the declarative-procedural distinction based on data from a variety of skill learning studies (Sun and Zhang, 2002). According to his model, declarative or explicit knowledge of how to perform the task is acquired in the initial stage of skill development, but becomes less relevant through practice, when the development of procedural knowledge allows the completion of tasks with little conscious awareness.

The distinction between *user mental model*: the mental model developed by the user, and *user model* is often drawn (Fischer, 2001; Norman, 1983; Preece, 1993; Benyon and Murray, 1993) (see Section 2.6.2). The user mental model is developed by the users during their interaction with the system, while a user model consists of "knowledge about the user, either explicitly or implicitly encoded, which is used by the system to improve the interaction" (Finin, 1989). A user model should relate to a user mental model: it extracts the relevant features of a user mental model which impact on system usability. In addition, these features should be addressed in the system design. Embedding the user model in the system means designing the system on the basis of a series of assumptions about user's knowledge, beliefs, intentions and behaviours. Thus, the user model is a simplified version, a schema of user mental model, which can be addressed by the system design (see Section 11.4.3).

Summarising different typologies of models, Grant (1990) introduced Wahlström's (1988) classification which distinguishes the following functions which the study of user mental models can serve:

- a means of communication,
- an aid to understanding,
- a tool for predicting and control, and
- a device for training.

The first two purposes of studying mental models refer to the general principles which underlie human cognition (e.g. thinking, reasoning, imagining etc). These ideas ought be communicated to the system designers and help psychologists extending their general understanding of human cognition. Grant (1990) quoted Young (1983) who suggested that user mental models "should help to explain aspects of the user's performance, learning and reasoning about a system, as well as providing guidelines for good design".

Understanding user mental models enables fruitful applications. Thus, some of the aspects embedded in user mental model, can be formalised and used for running simulation of user behaviour. Once aspects of the user mental model have been embedded in system design, they can be used to increase user's understanding of how the system works, or in other words to assist users in the training process for learning to use the system.

For the purpose of this thesis, I am interested in both theoretical and practical aspects which the study of mental model of navigation can support. Such study could increase our understanding in the area of spatial cognition by validating or refining the current theories and models of navigation. In particular, studying mental models of navigation can be harnessed for training navigation in VE, a technology through which the model has been investigated. However, the goal of training cannot be reduced to the specific VE used in this study; but the training is meant to allow users to navigate better in other VEs as well, or even in the real world. In other words, the main purpose of the training is to allow users to improve their spatial skills of exploring/searching a VE, where the VE itself is used only as a media. Using the VE for training low spatial users or poor navigators (see Section 5.4) can be achieved only through investigating user mental model of navigation and elaborating a user model of navigation. The latter, a simplified and schematic version of the former, encapsulates some rules and strategies which high spatial users or good navigators employ successfully in their navigation. Making these rules available to low spatial users lies at the core of training.

Given the significance of mental models in the interaction with systems, there has been an increased interest in developing techniques which would enable system designers to access user's mental models (Kieras and Bovair, 1984; Cañas et al., 2003). Such techniques would allow not only the evaluation of user's models but also the necessary adjustments for a better match between those models on the one hand, and the system and designer's model on the other hand. Unfortunately, despite the awareness of their need, most of the methods developed a decade ago do not provide reliable information about the mental representation held by the user (Sasse, 1991).

Studying Mental Models

A main justification in studying mental models relates to their capabilities to support the understanding and prediction of human behaviour. Despite the apparent inconsistency between the mental models and consequent behaviours, mental models nevertheless influence people's decisions (Goguen and Linde, 1993).

The techniques for studying users' mental models have a lot to gain from methods developed in social science. These methods vary on a continuum from direct elicitation methods, first to be employed, to indirect elicitation methods, particularly used for validating the proposed mental models. Reviewing the techniques employed for eliciting requirements engineering, whose basic question is how to find out what users need while interacting with a system, Goguen and Linde (1993) identified a comprehensive list consisting of: introspection, questionnaires, interviews, focus groups, protocol analysis, together with techniques from discourse analysis and discourse structure, like conversation and interaction analyses.

These techniques can be equally used for usability evaluation studies and for eliciting information about mental models. However, each of them has some limitations. These limitations are even stronger in the case of eliciting implicit knowledge: "... any attempt to use introspection in order to become conscious of something that is normally unconscious is unlikely to succeed" (Johnson-Laird, 1981). Questionnaires assume that a particular question always has the same meaning to subjects, excluding any possibility for establishing a shared meaning. This possibility is greater for interviews and focus groups, but these methods are more vulnerable to distortion by interviewer bias. Both questionnaire and interview techniques are vulnerable to post-rationalisation, in terms of suppressing the inconsistent beliefs in the favour of justifiable knowledge (Morgan et al., 1992). Protocol analysis (Ericcson and Simon, 1984) involves an artificial discourse form and none of these methods can elicit implicit knowledge, because people are often unable to fully articulate this knowledge.

Another problem associated with direct elicitation techniques relates to the character of models held by novices: they are locally coherent but globally inconsistent (Gentner, 2002) (see *collages* proposed by Tversky (1993) in Section 3.2.2). Users also hold several contradictory models of the same phenomenon, which increases the difficulty of their elicitation (Gentner, 2002).

In order to address some of the inherent limitations of the previously outlined direct methods for studying mental models, a new class of indirect methods has emerged. Some of these indirect methods consist of the analysis of behaviour, response time, eye movement or movement paths. Each of these techniques involves attempts to infer the mental model based on its externalisation. Given the significant role played by procedural knowledge in user's models and because of difficulties encountered for eliciting them, new techniques had to be considered.

Despite the controversial opinions which seem to excite, Parallel Distributed Processing (PDP) models seem relevant in this respect (Rumelhart et al., 1986). PDP is a class of neurally inspired information processing models (Slusarz and Sun, 2001, p. 952):

> The inaccessible nature of implicit knowledge may be captured by subsymbolic distributed representations provided by a backpropagation network.

The following section is dedicated entirely to connectionist models as an alternative way to investigate the implicit knowledge that would otherwise be difficult to formalise. Having reflected upon the pros and cons of this method, I argue for the suitability of such an approach for modelling in general and therefore, in the context of this thesis, for modelling spatial learning in VE and extracting some of the strategies governing spatial behaviour (see Section 6.4.1 and Chapter 8).

As highlighted in Section 3.2.4, addressing such implicit knowledge challenges the traditional techniques of knowledge elicitation. Because of their sensitivity to learning temporal sequences — navigation is after all a spatio-temporal process — connectionist models and in particular recurrent neural networks are particularly suitable for implicitly capturing navigational rules (Elman, 1990; Ellis and Humphreys, 1999; Ghiselli-Crippa, 2000).

Connectionist Models The place of connectionism in cognitive theory has been considerably debated within cognitive science (Fodor and Pylyshyn, 1988; Goldsmith, 1998; Medler and Dawson, 1998; Green, 1998; Greco, 1998). One major argument in this debate is related to the similarity between Artificial Neural Networks (ANNs) and their biological counterparts which have inspired ANNs. For this, it seems that connectionist models should only be interpreted as literal models of brain activity, and therefore contributing to cognitive theories only at the implementation level (Medler and Dawson, 1998).

The essence of connectionism, although inspired by real neural networks, represents a distillation of key structural and functional features of biological neural networks, free of morphological and physiological details (Opie, 1998; Dawson and Shamanski, 1994).

Highlighting the position of connectionism with respect to classical cognitive architectures, Reilly (1991) pointed out that while classic approaches to cognitive science offer a symbolic macrostructural description of cognitive phenomena, connectionism, without invalidating this position, sees this macrostructure as an "emergent property of the activity of a connectionist microstructure".

The process of abstraction is not inconsistent with a realistic interpretation of connectionist models. Connectionist models are best understood as realistic treatments of certain (high level) structural features of the brain (Opie, 1998).

Reilly (1991) considered connectionist models to be "loosely constrained by considerations of neural plausibility", being merely schemata of brain functioning. However, the numerous differences between biological neural networks do not imply that connectionist models are not scientific models (Lee and Heuveln, 1998). From this perspective, the current connectionist models are closer to the traditional symbolic paradigm than to the neural level (Smolensky, 1987).

Another argument advocating connectionism consists of the power of network interpretation (Elman, 1990; Rumelhart et al., 1986; Plunkett and Elman, 1997; Goldsmith, 1998; Hanson and Burr, 1990; Ellis and Humphreys, 1999; Reilly, 1991; Lee and Heuveln, 1998; O'Brien, 1998). Despite its significance, this line of research did not lead yet at a complete understanding of the principles underlying connectionist architectures (Goldsmith, 1998).

The potential residing in the analysis of internal structure of the network can be harnessed for producing new cognitive theories that are more than implementations of classical ones (Medler and Dawson, 1998). In this way, the investigation of properties of ANNs can be valuable for the study of cognition, irrespective of whether and how those capacities and properties are realised in the brain (Goldsmith, 1998). Such post hoc analysis, particularly over the hidden units "can clarify imprecise or incomplete models of psychological phenomena and can help reveal important relations between learning representations that are not taken into account in the rule-based approach" (Hanson and Burr, 1990).

One of the limitations representing a substantial impediment to connectionism was its inability to deal with temporal phenomena in general, and with sequences in particular (Reilly, 1991). Several arguments addressed such limitations. Influential work by Elman (1990) proposed the representation of temporal dimension directly in the network (Reilly, 1991; Plunkett and Elman, 1997) (see Section 6.4.1).

In addition to embedding *time* in connectionist architectures through recurrent neural networks, Elman's work has shown how temporal sequences can be learned and predicted by such nets. In addition, he demonstrated how in learning temporal sequences, "models can develop sensitivity to high order regularities in the training environment", such as syntactic categories of words (Ellis and Humphreys, 1999).

Because of this sensitivity to frequency and co-occurrence statistics in training sets, connectionism offers a major benefit which is exploited within this thesis. Stressing the role of connectionist models in understanding spatial learning, Crippa (2000) noted that: "... being systems that learn, they can therefore be used to model and study the process of learning spatial information".

To conclude, there are four important aspects which support the connectionist approach to modelling navigation.

- It has to do with the spatio-temporal nature of navigation process. For this, the particular ability of RNNs to learn temporal sequences represents a major advantage.
- Extracting knowledge from the trained RNNs, which have learned to predict the users' trajectory, allows exploring the regularities, implicitly embedded in the trajectory paths. Such regularities can be expressed in terms of rules governing spatial behaviour (Psarrou and Buxton, 1994).
- Implicitly capturing the navigational rules embedded in movement paths is an unobtrusive process which involves the analysis of user's behaviour rather than user's introspection.
- The potential of ANNs to generalise can be particularly harnessed for providing real time navigation support in dynamically reconfigured VEs. In adaptive VEs designed for navigation support, RNNs can be used to predict a user's movement trajectory. The accuracy of a user's path prediction determines the accuracy of the implemented strategies which are meant to exploit and/or augment users' knowledge and skills (Chen et al., 2000) (see Section 2.6.3).

In addition, connectionist modelling of navigation has been successfully applied to mobile robots. Such modelling aiming to provide autonomy to mobile robots has increased considerably over the last decade (Meng and Kak, 1993; Nehmzow, 1992; Nolfi and Tani, 1999). Nolfi and Tani (1999) employed RNNs to investigate how prediction learning can extract regularities from the external environment, in the case of a mobile robot that navigates in a simple environment divided into two rooms.

Given its complexity, navigation remains one of the most challenging functions to be performed by mobile robots, since it involves: sensing, acting, planning, architectures, hardware, computational efficiencies, and problem solving (Murphy, 2000). I believe that this field of research can provide useful insights into the study of human spatial behaviour.

However, despite the apparent similarities, the approach employed in this thesis is qualitatively different. Given the infancy of this field of research, most of the attention has been captured by solving the highly demanding technical aspects of designing and building such robots. Such kind of constraints limit the complexity of navigation techniques employed by robots. In the context of human navigation, aspects like vision, locomotion, obstacle avoidance, object recognition etc., are usually taken for granted, and therefore considered low-level processes, needed to support but not to successfully perform complex navigation tasks. Consequently, despite their computational complexity, the navigation strategies employed by robots, such as wall following, are rather simplistic and trivial. In contrast, humans employ more advanced heuristics, whose investigation positions this work on a different track than similar studies in the field of robot navigation. An appealing future research direction aims to bridge the gap between these two fields: human and robot navigation, by employing successful human spatial heuristics for improving robot navigation.

Mental models have been applied in a large variety of domains with the purpose of highlighting the representations that people hold with respect to phenomena, systems, situations (Forbus, 1984). They have also been applied to spatial representation and navigation (Hutchins, 1983; Tversky, 1991).

3.2.2 Spatial Mental Models

Any review of spatial mental models should begin with some conceptual delimitations. This section introduces several definitions of spatial representations, which have been summarised by Hart and Moore (1973):

- reflection of space in the minds of man (Shemyakin, 1962);
- symbolic and internalised mental reflection of spatial action (Piaget and Inhelder, 1967);
- implicit action which is carried out in thought on the symbolized object (Laurendau and Pinard, 1970);
- internalised cognitive representation of space (Hart and Moore, 1973).

Apart from enabling a gradual introduction to this topic, these definitions offer also a basis for presenting different types of spatial mental representations which will be further detailed (Section 3.2.2). Before this, some conceptual delimitations related to the *system of reference* are introduced. System of reference is an essential element of spatial representations which spatially orients the individual in some systematic manner to the environment (Lee, 1973). It is a means of representing the locations of entities in space (Klatzky, 1998). As mentioned in the following Section 3.2.3, the development process includes landmark, route and survey level knowledge. The learner will develop a metric internal representation of space, through stages of *egocentric* to *allocentric* knowledge (Lee, 1973). In the egocentric reference frame, also called geocentric, locations are represented with respect to the particular perspective of a perceiver, whereas an allocentric reference frame locates points within a framework external to the holder of the representation and independent of his or her position (Klatzky, 1998).

Two basic concepts usually mentioned in describing spatial behaviour are heading and bearing (Figure 3.2). An object's heading is the angle between the object's axis of orientation and some reference direction external to the object. The bearing from an object to a point A is the angle between the object's axis of orientation and a line from the object to the point A. The course represents the direction of travel over the past few occupied locations (Klatzky, 1998).

Spatial representations can take different forms, according to the properties they hold and the operations involved in their acquisition. Probably the best documented type of spatial representations is a *cognitive map*.

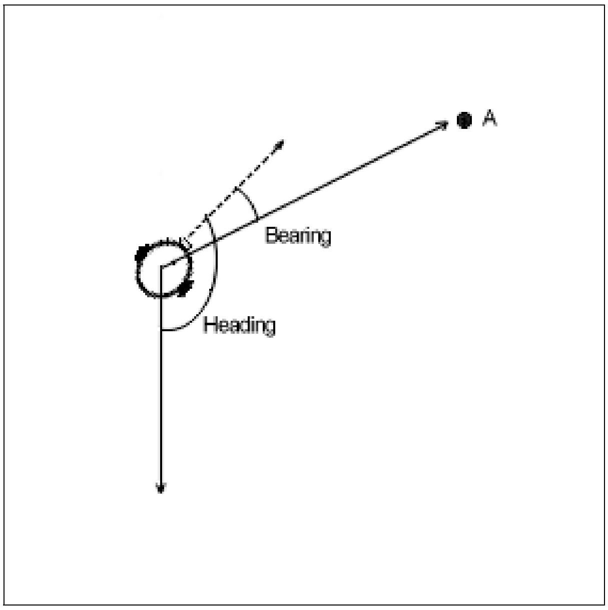

Figure 3.2: Basic Terms Used for Describing Spatial Behaviour

Cognitive Maps

The concept of the cognitive map was coined by Tolman (1948) who suggested that the goal-finding behaviour which rats seem to exhibit for food finding in a maze can be explained through the use of an *internal map-like representation of space.* Cognitive maps have been defined as:

- mental models and the internal representation of reality in a structured way (Tversky, 1993);
- maplike representations of geographic or other large-scale environments (Hart and Moore, 1973);
- cognitive representations of geographical space (Stea and Blaut, 1973);
- internal representation of perceived environmental features or objects and the spatial relations among them (Golledge, 1999);
- representation of a group of places, some related to others by means of a set of rules of spatial transformation (O'Keefe and Nadel, 1978).

Despite several definitions which have been proposed in the attempt to capture their meaning, cognitive maps present a series of interesting properties which are commonly accepted. They define boundaries of places of interest, integrate separately learned routes into a configuration as a whole and allow an overview, the so-called bird's eye view (Golledge, 1999). As with any other types of representations cognitive maps are complex, highly selective, abstract and generalised representations which bear merely a functional analogy with the environment which inspired them (Downs and Stea, 1973). They are maplike mental constructs that can be mentally inspected (Tversky, 1993).

Kaplan (1973) summarised these characteristics of cognitive maps as generality, additional properties and emergent functions. Their generality results from the common structures that cognitive maps share with other cognitive processes and functions. The basic components of cognitive maps are organised in an emergent hierarchical structure which ensures flexibility, anticipation and decision making in the space of future potential events.

The spatial representations embedded in cognitive maps serve the ultimate goal of surviving since the “environment is rich, diverse and uncertain while the organism has limited time and storage capacities in his head” (Kaplan, 1973). This ultimate aim can be broken down into several functions. Kuipers (1977) identified three such functions: the assimilation of new information about the environment, the representation of the current position, and answering to route-finding and relative-position problems. In a similar way, Terrazas (2000) considered the following three cognitive functions of cognitive maps: shortcut taking, detection of environmental novelty and memory for events in their spatial contexts. In addition, cognitive maps can support direction giving, memory for places, data organisation and wayfinding (Tuan, 1975). Given the different functions they serve, one of the main characteristics of cognitive maps has been considered being their great flexibility (Rodrigo, 2002).

It is interesting to briefly mention at this point the two approaches developed in the area of robot navigation: metric and topological navigation. *Metric navigation* is concerned with techniques aimed to produce an optimal path. *Topological navigation* focuses on producing a route with identifiable landmarks and gateways, where a robot can change its heading. The optimal path, usually not considered optimal by human standards, involves *a priori* knowledge of the spatial layout, for producing and comparing all possible paths (Murphy, 2000). This line of research represents a distinct direction than the one adapted in this thesis.

Despite their features which enable a rich and meaningful set of functions previously outlined, cognitive maps have also some limitations. They are incomplete, distorted, schematised, and augmented (Downs and Stea, 1973). Some of these limitations of cognitive maps can be addressed by other mental representation metaphors. Tversky (1993) suggested *collages* and *spatial mental models.* Collages are disparate pieces of knowledge about environment which lack the coherence assumed by cognitive maps but contain partial information and differing perspective. The existence of collages could lead to conflict when two different maps overlap on the same problem the brain is trying to solve. Spatial mental models preserve coherently the topological relationships between elements characterising a familiar environment and allow perspective-taking, reorientation and spatial inferences.

The following section provides an insight into the acquisition of spatial mental models, or in other words, into the spatial learning process. This aspect received a great deal of attention from psychology which provided several symbolic models of navigation. The increased technological development in brain scanning techniques fosters an interesting line of research in the field of neuroscience, from which another set of models of navigation have emerged.

3.2.3 Acquiring Spatial Knowledge

The process of developing cognitive maps is called *cognitive mapping* (Stea and Blaut, 1973). There seems to be a commonly accepted idea regarding the gradual acquisition of cognitive maps, as opposed to their innate character (Hart and Moore, 1973; Tversky, 1993; Lee, 1973). The innate aspect of cognitive maps resides in the cognitive structures and functions which support their acquisition: "man could not be born with the maps he needs ... rather man must be born with a tremendous propensity to make and extend maps; that is to explore and learn" (Kaplan, 1973).

The study of navigation in the area of HCI has developed mostly in the field of cognitive modelling, benefiting from inputs provided by both environmental psychology (Piaget and Inhelder, 1967) and geography (Lynch, 1960). The most relevant models of navigation, focused particularly on spatial knowledge acquisition are outlined below. The presented taxonomy is based on the one developed by Montello (2003).

Symbolic Models of Navigation Attempts to understand spatial behaviour in both real and artificial worlds were primarily concerned with highlighting the symbolic representation of spatial knowledge.

Seminal in the field of studying the acquisition of spatial knowledge is the work carried out by Piaget and Inhelder (1967) which led to a theory of the development of the concept of space. They were the first to acknowledge the importance of moving in space and experiencing with objects, through coordination and internalisation of actions for the development of early spatial representations. Piaget and Inhelder (1967) showed that the child's initial understanding of space is topological, and is sensitive to simple qualitative relations like proximity, order, enclosure and continuity, whereas the Euclidean spatial relationships, for example angularity, parallelism and distance are understood later (Lee, 1973).

The Landmark-Route-Survey (LRS) model of cognitive mapping (Siegel and White, 1975; Thorndyke and Hayes-Roth, 1982) is one of the most widely accepted models designed to explain the adults' acquisition of spatial knowledge, in the form of a developmental sequence.

Landmark knowledge consists of information about discrete features in the environment, such as objects or places, identified and remembered because of their features: distinctiveness, location, personal significance assigned to them etc. Landmarks are conceptually and perceptually distinct locations (Jul and Furnas, 1997) used as a basis for judgements about different aspects of the layout (Sjölinder, 1998). They could mark a decision point, and be relevant in wayfinding. One of the most important roles played by landmarks is that of symbolising *anchor points* for organising the information within the spatial layout (Golledge, 1999).

Once landmark knowledge has been acquired, individuals start developing information about possible spatial and temporal connections between specific environmental features, connections which represent route knowledge (Allen, 1982). Golledge (1999) defined route knowledge as the procedural knowledge required to navigate along a route or path between landmarks or distant locations. Integration and inferences are the key concepts which distinguish landmark and route phases from the survey phase. In any of the initial two phases one can integrate or make inferences from the discrete information about the basic knowledge units: landmarks for the first stage and routes for the second one. Initially, the information characterising route knowledge holds only topological features (ordered locations of landmarks along a route), but lacks metric information between these landmarks. The development of route knowledge leads to an increased amount of information about the relationships between the landmarks on a route, in terms of landmarks' order, approximate distance between them or length of the entire route.

Route knowledge is limited to the knowledge of sequential locations without knowledge of general relations, which defines survey knowledge. Survey representations often show a hierarchical structure (Tversky, 1991). Survey knowledge represents the highest level of spatial knowledge, a map-like mental encoding which integrates both landmarks and route knowledge. Reaching this level enables an individual to make inferences about both landmarks and routes, based on a thorough understanding of the interrelationships between them. Only survey knowledge enables an organism to plan different routes on paths not yet travelled (Werner et al., 1998) or to locate objects within a general frame of reference (Mecklenbräuker et al., 1998).

Despite its large acceptance (Tversky, 1993; Rothkegel et al., 1998; Werner et al., 1998), this model of spatial knowledge acquisition received amendments for its simplistic view. Alternatively, Montello (1998) proposed five stages. The first one consists of a mixture of landmarks and route knowledge (including metric knowledge) which increases in quantity, accuracy and completeness during the second stage. The third stage, which assumes the integration of discrete places into a hierarchical structure, represents a qualitatively different level. The fourth stage acknowledges the role of individual differences in spatial knowledge acquisition, while the last one emphasises the role of spatial language for topological knowledge, which exists independently of metric spatial knowledge.

Investigating the manner in which people understand the layout of an urban place, Lynch (1960) identified a set of elements which describe the skeleton of a city: paths, edges, districts, nodes and landmarks. Paths are familiar major or minor routes used for travelling, such as streets, railroads, walkways etc. District or neighbourhood is an area which can be recognised as distinct on the basis of its internal homogeneity. Edges are boundaries dividing districts, while landmarks are external points of reference, such as physical objects which act as orientation aids. Nodes are strategic points, such as important crossroads, which differ from landmarks in their function: nodes are points of activity rather than physical objects.

Focusing on learning strategies which can be employed for learning a novel environment, Golledge (1999) identified the following three: the active search and exploration according to a specific rules or heuristics, the prior familiarisation with secondary information sources about the environment, and the controlled navigation practices such as path integration, boundary following, sequenced neighbourhood search.

The work of Kuipers (1978) marked a starting point for a computational theory of wayfinding (Raubal and Worboys, 1999). Kuipers proposed TOUR (Kuipers, 1978), a computational model of navigation which has been extended through the Spatial Semantic Hierarchy (SSH) (Kuipers, 2000). SSH is a model of large-scale space which posits four interacting representations, inspired by the properties of the human cognitive map:

- *Control level* is based on sensorimotor interaction with the world described by control laws which lead to distinctive states. The SSH model shows how the control laws guide the experience which leads to the acquisition of the cognitive maps.
- *Causal level* associates actions for moving from one state to another.
- *Topological level* offers a qualitative representation of the world in terms of places, paths and regions which are used to explain the states and actions previously defined.
- *Metrical level* involves distances and directions in representing the external world, which appears organised into a single global frame of reference.

Another direction of research has emerged in the field of neuroscience. Studies in this field try to address four main questions such as “how spatial information relevant to navigation is encoded in nervous systems, which brain areas process navigation information for navigation, how sensory information for navigation is integrated in the nervous system, and how particular injuries or organic syndromes produce particular deficits in spatial behaviour” (Montello, 2003).

Models of Navigation Inspired by Neuroscience All models of navigation inspired by research in the neuroscience field have emphasised the role of hippocampus in spatial learning (O’Keefe and Nadel, 1978; Taube et al., 1990; Arleo et al., 2000). Experiments on rats navigating in mazes revealed *place cells* in rats’ hippocampus which fire preferentially when the rat is in a particular location (O’Keefe and Nadel, 1978). These cells are independent of the rat’s heading as long as distal cues persist in defining a location. Another type of cells, *head direction cells* fire preferably when the rat is heading in a certain direction, regardless of its position (Taube et al., 1990).

A remarkable theory of spatial behaviour was developed by O’Keefe and Nadel (1978) on the basis of Tolman’s findings (1948). Tolman trained rats to find food using an indirect route. When this route was blocked, the rats followed more often the direct route than the other indirect available routes. These findings suggest that such behaviour has not been behaviouristically learned, but rats succeeded to build and use an internal representation of the environment which helps them in wayfinding. O'Keefe and Nadel (1978) identified the following types of spatial learning:

- *Place learning* which ensures a spatial representation in allocentric coordinates of the spatial layout (i.e. cognitive map), by encoding the distal stimuli and their interconnections.
- *Route learning* relates to the acquisition of landmarks significant for the goals.
- *Response learning* depends on the proprioceptive, kinaesthetic and vestibular cues (Leplow et al., 1998).

The benefits of each of these models for understanding spatial learning cannot be overestimated. Whether they focus on behavioural aspects or on the functional principles of the brain, these models provide a coherent background for further research. However, as with any models, they provide a high level explanation of how the spatial learning process occurred in humans. Despite the fact that this process is seen in the larger framework of human action, usually tied to the spatial layout of the environment where the action occurs, these models also have limitations.

They fail to provide insights into the understanding of how successful spatial learning occurs, in terms of low-level rules which would define efficient spatial behaviours. Usually successful spatial learning is simply seen as leading to a better, comprehensive and well articulated cognitive map. Despite its significance, the inherently hidden character of any representation and in particular cognitive maps, raises a complete new set of problems needing to be investigated. The following section addresses some of these problems and the methods developed for eliciting spatial mental models.

3.2.4 Eliciting Spatial Knowledge

The two basic components involved in navigation seem to rely differentially on declarative and nondeclarative knowledge (Montello, 2003). Thus, locomotion requires usually nondeclarative knowledge of procedural skills. Such knowledge is *impenetrable* and is acquired without awareness. In contrast, wayfinding skills are usually penetrable and the declarative knowledge defining them can be directly learned and reported (Montello, 2003).

Before reviewing the classical methods used for eliciting information about spatial representations, a distinction should be made between external representations, internal cognitive representations and spatial behaviour (Hart and Moore, 1973). Representations are external or internal according to where they take place: outside or inside the mind. External representations are knowledge and structure in the environment in both linguistic and graphical modalities (Suwa and Tversky, 2002; Tversky and Lee, 1999), while internal representations are knowledge and structure stored in memory, such as propositions, deduction, and schema (Zhang, 1997).

External representations usually capture the declarative (known as objective or explicit) knowledge which can be entirely communicated, in a symbolic form, and understood by the recipient (Ambrosini and Bowman, 2001). Externalising internal representations can be done in various forms by employing:

- verbal techniques (Darken and Sibert, 1996b), or
- graphical techniques such as sketching (Lynch, 1960) or drawing maps (Tversky and Lee, 1999).

Among verbal techniques, probably the most frequently employed is that of "thinking-aloud" during a problem solving task. It relies heavily on subjects' ability to verbalise their thoughts as they interact with the system or to articulate their knowledge in response to direct questions (Hudlicka, 1996). The data collected in this way can be processed through protocol analysis (Ericcson and Simon, 1984).

Graphical techniques of eliciting spatial information consist of asking the participants to draw a map of the environment about which they were expected to acquire spatial knowledge (Tversky and Lee, 1999). In *The Image of the City*, Lynch (1960) was the first to propose the utility of sketch maps for obtaining insights into how people mentally structure the spatial layout of a city. Unfortunately, there are many limitations in the use of drawings for inferring the nature of internal representations, mainly because of the dimensionality reduction (Lee, 1973) and of the lack of methodology for processing such data. In addition, both verbal and graphical techniques are limited by their inner nature: they assume a particular level of verbal skills, in particular introspection, and drawing skills respectively. Limited user capabilities lead to inadequate external representations, despite the fact that the internal representation held by the user could be quite accurate.

Many other tasks have been used to study spatial representations: distance estimations, location and orientation judgments, recalling the routes travelled, recognition of sequences of route segments, recording behaviour traces through an environment, spatial tasks (Satalich, 1995; Golledge, 1999).

Once externalised it is possible to check the accuracy of the externalisation against the objective reality, depending on the appropriateness of the mode chosen to express spatial information (Golledge, 1999). Direct modalities of assessing navigation relying on measures taken after learning has been completed, fail to capture the temporal dimension embedded in the learning process (Rowe et al., 1996). Despite their variability, external representations are only of interest to the degree that they shed light on the development of the internal representation of space (Hart and Moore, 1973).

Internal representations are more difficult to capture and usually they reflect implicit knowledge. Due to its hidden aspect, implicit knowledge raises serious challenges which explain the limited number of empirical attempts investigating them (Ambrosini and Bowman, 2001). Such problems are known as *knowledge elicitation bottleneck*: the implicit knowledge is difficult to articulate and express directly and often idiosyncratic or difficult to justify (Berry, 1987).

The problems relating to elicitation of implicit knowledge have been addressed through techniques developed in the field of experimental psychology, designed to access the internal mental models (Hudlicka, 1996; Turban and Aronson, 1998). Such indirect methods of elicitation assume that relevant knowledge is not easily accessible to conscious thought and cannot therefore be revealed by simple introspection.

This thesis proposes a novel method for addressing the implicit knowledge embedded in mental spatial representations employing techniques from machine learning (see Chapter 6). At the best of my knowledge, such a methodology has never been used before. It seeks to overcome the limitations outlined above relating to implicit knowledge elicitation. This approach is objective, involving the analysis of user behaviour rather than his/her subjective thoughts. It is unobtrusive, since it requires no additional involvement of the users, and even more importantly, it can be employed during task completion. The dynamics of user's behaviour can be captured on-line, a fact which ensures system capacity to dynamically adapt to the user's navigational model. Another advantage of this method consists of enabling automatic discrimination of users and automatic tailoring of the system to different user groups. The goal of this approach is to extract rules and strategies defining spatial behaviour within a VE. A rule stands for the relationship among concepts, and is usually expressed as "if–then" statement (Gagné and Briggs, 1974). Strategy, whose etymology should be seen in military sense (*stratego*: army leadership) means the preparation and implementation of plans in order to achieve some predefined goals with the efficient use of the existing resources. Following from here, the term "cognitive strategy", coined by Alley and Deshler (1979) refers to "techniques, principles, or rules that facilitate the acquisition, manipulation, integration, storage, and retrieval of information across situations and settings".

Introduced above are the major aspects related to spatial learning that have resulted from theoretical and empirical studies of human navigation in real worlds. The following section establishes the connection to navigation in VEs.

3.3 Navigation in Virtual Environments

This section introduces some of the relevant aspects which concern navigation performed in VEs. The dissimilarities between the VEs and the real world that impact on spatial performance in VEs, are currently not well enough understood. This establishes the need for a better understanding of navigation process (Darken et al., 1998). The section starts by outlining some taxonomies of spatial behaviours in VEs. In a particular focus of attention are the individual differences in navigation in VEs which impact on both spatial behaviour and spatial performance. I conjecture that this impact can be partly explained through the different navigational patterns or rules associated with the spatial behaviour.

3.3.1 Navigational Behaviours

Krieg et al. (1998) proposed a hierarchical taxonomy of different spatial behaviours associated with different spatial knowledge representations. This taxonomy could be applied to animal and human behaviour, as well as to biologically inspired robots, since they share the essential navigational issues. The taxonomy attempts to map the levels of knowledge acquisition from LRS model (Siegel and White, 1975) (see Section 3.2.3) to the hierarchy levels of spatial behaviours: basic behaviours (around landmarks) are represented as elementary tactics, route knowledge is reflected in some tactical navigation, and survey knowledge comes in at the level of strategic navigation.

Basic behaviours are the simplest tactics to be investigated and implemented in robots. Krieg et al. (1998) distinguished two important features of the spatial layout impacting on these behaviours: the open or enclosed space and the network of passages (Table 3.1).

Table 3.1: Basic Navigation Behaviours

Title	**Percept**	**Representation**	**Action**
Approaching Target			
reaching target	remaining distance	distance	when remaining distance near zero, triggers new behaviour
heading for target	view (of target)	designated view	when view corresponds to designated view, triggers new behaviour
stopping			stop (at target)
Basic behaviour in (enclosed or open) space			
course following	course orientation	course direction	adjust orientation to course, steer clear of obstacles
docking at target	pos., orient. relative to target	designated target pos., orient.	manoeuvre into target pos. and orient.
Basic behaviour in network of passages			
passage following	walls obstacles		follow passages centred between walls, avoiding obstacles
wall following {left-right}	wall, corners obstacles	left-right	follow left-right wall (around corners) avoiding obstacle
turning into a passage	junction with n branches	branch designator	turning into designated passage

A taxonomy like the one outlined above offers a good starting point for a better understanding of spatial behaviour. However, it groups different spatial behaviours without referring in which way or in which conditions these behaviours can be identified as efficient, and accordingly used to build navigable VEs. The following section introduces individual differences usually investigated with respect to navigation in VEs.

3.3.2 Individual Differences in Navigating in VEs

While a considerable amount of work has concerned the technological factors involved in the design of VEs — factors which might be related to the training effectiveness — little research has been done in the field of user's characteristics. As Waller (2000) highlighted, this is unfortunate since individual differences are a major source of variation in performance in both real and virtual spatial tasks, accounting for more variation than the design of VE or the employed training procedures. Further, Waller noted that since the inter-subject variability in performance within a VE is higher than that for the analogous real tasks, it seems that the knowledge acquired within a VE requires not only abilities for similar real tasks, but additional skills as well.

Individual differences in spatial learning usually include spatial abilities, gender, and prior experience in Human–Computer Interaction (HCI) (Waller, 2000). This set of individual differences has been expanded to personality, cognitive style or learning style when applied to spatial tasks for information retrieval (Chen et al., 2000; Chen and Rada, 1996). A meta-analysis of studies on individual differences in using hypertext systems revealed that high spatial individuals, namely those who performed better in spatial ability tests, are able to build a cognitive map of the informational structure easier than low spatial users (Chen and Rada, 1996; Chen et al., 2000).

Spatial abilities consist essentially of two dimensions: *spatial visualisation* which is the ability to mentally manipulate objects without reference to oneself, and *spatial orientation* which involves self as a reference point (McGee, 1979). The second dimension is usually measured with the Guilford Zimmerman Spatial Orientation test (Guilford and Zimmerman, 1948). Unfortunately, there are some limitations in psychometric tests for predicting the environmental learning in the real world, and consequently, the strength of relationship between spatial ability and spatial knowledge acquisition in VE is also ambiguous (Waller, 2000). An alternative method of assessing spatial abilities in VE is through the level of spatial knowledge acquisition in the real-world environments (Waller, 2000).

Following this direction, it is conjectured that the success in search tasks can be perceived as an indicator of high spatial abilities, mediated by the success in acquiring spatial knowledge about the visited environment.

Gender effects on spatial abilities has been largely acknowledged in both spatial learning in real world and psychometrically-assessed spatial abilities, findings indicating that usually men outperform women (Waller, 2000). The majority of findings described females as tending to use landmarks to navigate, whereas males tend to use broader bearings (Czerwinski et al., 2002). Such gender differences seem to agree with the possible theory that evolutionarily, many of these abilities would have been important for survival in the time of hunter-gatherer societies, where males navigated unfamiliar terrain while hunting, and females foraged more nearby areas gathering food (Weiman, 2003). This gap is even larger when it comes to gender differences in spatial knowledge acquisition in VEs.

There is some evidence that this greater gender effect is due to the gender differences in the abilities required for interacting with computers (Waller et al., 1998; Sas et al., 2003a). Waller et al. (1998) found significant gender effects on performance in VEs, despite the fact that while trained in real world environments women performed nearly as well as similarly trained men. Therefore, the previously identified gender effect in VE training seems to be caused not by the differences in spatial knowledge acquisition but in the effectiveness of VE for training. In the same line of research, manipulating display design Czerwinski et al. (2002) found that wide fields of view on a large display almost eliminate the gender differences in spatial tasks on a desktop VE. This is assumed to be caused by the reduced cognitive overload of building the cognitive map which frees the cognitive resources and endorses an optimised landmark navigation.

Experience in HCI has been considered as another factor contributing to the performance of spatial tasks in VEs. Waller (2000) identified its three dimensions in terms of experience with computers in general, attitudes towards computers and proficiency with the interface. A comprehensive study on individual differences was performed by Waller (2000) who examined the role of user characteristics and abilities in determining the effectiveness of computer-generated environments (e.g. desktop VEs) for training spatial knowledge. The explored factors are: spatial abilities measured with psychometric tests, ability to form an accurate representation of a real environment, gender, computer attitudes and experience, proficiency with the navigational interface, and the ability to acquire and transfer spatial knowledge from a VE to real world. Spatial ability correlates significantly with spatial knowledge acquisition in a VE but not in the real world. Spatial knowledge acquisition in VE is predicted by the proficiency with navigational interface and spatial ability. The effect of gender is influential on spatial tasks, particularly through its relationship with interface proficiency and spatial abilities. These findings suggest that individual differences between users may account for more variance in performance than differences in system design.

Compared to the limited number of studies focusing on individual differences in navigating in VEs, more research studies emphasising also the user model of navigation have been carried out in the field of information systems (Ford et al., 1995; Chen and Ford, 1997; Ford, 2000; Ellis et al., 1992; Berendt and Brenstein, 2001). Since the work in this area comes closer to my approach of investigating spatial navigation, a brief review of the most relevant results is outlined below, in an attempt to provide some additional insights for the topic of this thesis.

Individual Differences in Navigating in Hypermedia

Given the huge amount of information resources available on the Wide World Web, their potential for exploitation might be limited by the inefficient navigational strategies employed by people while searching for information of interest (Chen et al., 2000). This reason, reinforced by economical issues fostered a great interest in the area of information retrieval. Much work has been focused on the principles of designing easy-to-navigate web sites (Nielsen, 2000). In an effort to increase the effectiveness of the use of hypertext systems, the focus of recent research has shifted from systems to users (Ford, 2000). A fruitful line of research addresses this imperative, for better design of web sites, by focusing on the individual differences in search strategies and on possible ways of accommodating them (Ford et al., 1995; Chen and Ford, 1997; Ford, 2000; Ellis et al., 1992; Chen et al., 2000; Berendt and Brenstein, 2001).

Some interesting and promising studies (Ford, 2000; Ellis et al., 1992) focused on the individual differences reflected in navigation strategies. The authors investigated the relationship between the use of different navigational tools and strategies employed by users while they searched a large hypertext-based database. The navigational tools which were considered consisted of a global concept map, keyword index, menus, and a backtracking facility. With respect to the search strategies, the authors refer to Pasks (1988) work on holist and serialist strategies and associated styles of information processing. Therefore, the search strategies have been mapped to the style of information processing, measured by the Study Preference Questionnaire (Ford, 1985). Study findings indicate a significant impact of search strategies on the use of navigational tools. Thus, holists used concept maps more often, an aspect which enables global orientation and awareness of one's position in the entire informational structure, while serialists used more often the keyword index, particularly suited for finding specific information.

Despite the similarities between navigation in VEs and navigation in hypermedia, there are also inherent differences between these two types of navigation. The differences are rooted in the structure of information which leads to only a *metaphorical cognitive map* (Montello, 2003) in the case of hypertext navigation, as opposed to cognitive maps derived from physical environment. Nevertheless, the findings on spatial behaviour in the abstract spaces of informational systems provide additional insights in the understanding of spatial navigation.

Extensive studies on individual differences in VE spatial learning not only can advance our understanding of the psychological processes underlying spatial knowledge acquisition, but such research could also lead to more accessible and widely applicable systems for training and teaching, aimed to accommodate these large individual differences (Waller, 2000). The three most powerful predictors of spatial knowledge acquisition in a VE: spatial ability, interface proficiency and gender, collectively were able to account for almost 25% of the variance in measure of VE spatial knowledge. Despite the significance of this result, there is still a large portion of unexplained variance to foster further research in the field of individual differences (Waller, 2000).

I suggest that navigational strategies which can be inferred from navigational patterns could be responsible for this unexplained variance. This is one of the hypotheses which this thesis aims to investigate. The fact that different navigational patterns, probably rooted in different navigational styles impact significantly on the spatial learning has been already suggested by studies in hypermedia.

3.3.3 Navigable Virtual Environments

Much research has been focused on investigating those characteristics of VEs which impact on navigation training and in particular on the effectiveness of transfer from VEs to the real world (for a review see Waller et al. (1998)). This line of research was primarily concerned with manipulation of the technical aspects of VE design such as fidelity or realism of the interface, quality of VE and training time, or presence of additional navigational cues (Waller, 2000; Darken and Banker, 1998). Such a line of research could greatly benefit from the insights into the psychology of individual differences. Surprisingly, very few studies in the field exploited these insights. The main application areas of such work are military training (Darken and Banker, 1998) or fire-fighters training (Bliss et al., 1997), where the main purpose is the acquisition of spatial characteristics of the VE (Waller, 2000).

Darken and Sibert (1996a) analysed the spatial behaviour in large scale VEs, investigating the impact of different navigation assistance tools such as map, grid, and map and grid. Their findings indicated the superiority of a map as navigational tool against both control group and the groups exposed to the grid condition. The latter enabled superior directional information. The most important outcome of this study is that designing the VE according to the design principles governing the real world, supports improved performance on spatial tasks. Such design principles, inspired by Lynch's work (1960), refer to organisational elements of the environmental design, which serve to divide a space into a set of smaller and connected parts.

This study is unique, being one of the few which try to apply models of navigation in designing VE for navigation support. Navigation support is given through well organised environmental information; this organisation respects either the stages of acquiring spatial knowledge, or the design principles in the physical world. Such an organisation could only enhance users' spatial learning. But spatial knowledge acquisition is a complex process emerging from both environmental, external information and internal information, such as navigational knowledge and skills which are part of our surviving repertoire (Kaplan, 1973). The actual behaviours and strategies associated with environmental information are something that this study did not address.

The study carried out by Darken and Banker (1998) involves three conditions consisting of manipulating some navigational information during the wayfinding: map, map and high fidelity VE, and use of map in the real world. During the testing phase subjects were asked to find some targets such as nine control points placed in the real environment. Participants were assigned to conditions according to their level of experience in orienteering. Findings suggest that navigational ability is more important than training method with the VE, which proved to be more effective for intermediate orienteers as compared to advanced or beginner orienteers. The high fidelity of VE conveys redundantly navigational cues which help intermediate orienteers but not the advanced ones.

Two important conclusions emerge from this study. These results emphasise an idea developed within this thesis that individual differences play a significant role when it comes to assessing training performance, compared to the media which provides the training. In addition, research findings strongly suggest that training navigation should be done differentially, according to the degree of expertise or performance in spatial tasks. One limitation of this study consists of the relatively small sample size (15 participants) and accordingly an even smaller number of subjects assigned to each condition. The strength of this study consists of its power of exploration or discovery rather than in its power of generalisation.

Waller (1998) investigated the efficacy of tutorials developed with different media such as paper, video and VE for training the ability to solve a spatial puzzle. The group exposed to VE spent more time for training but this reflected in significantly better retention of the task solution.

The major outcome of this study emphasises the efficacy of VE for training spatial abilities, such as those involved in a spatial puzzle. This suggests that such spatial tasks are particularly suitable for use in training in VEs, probably due to the interaction and manipulation enabled by the VE medium. Unfortunately, no information is provided with respect to the training procedure, apart from that is has been carried out according to principles of tutorial design. A detailed description of the spatial problem solving strategies which the tutorials tried to convey, and the way in which such strategies have been previously identified, represent interesting issues which this paper does not capture. In addition, once the potential of VEs for solving such tasks has been suggested, investigating different possible approaches of using VEs for training the skills required by these tasks requests future investigation.

Dijk and his colleagues (2003) worked on developing forms of navigation assistance to enable novice users of a VE to increase their performance on wayfinding tasks. The VE represents a virtual theatre that models a real musical theatre. The explored form of navigation assistance consisted of the use of personal agents. The authors developed three personal agents. One agent offers advices regarding recent available information about the VE, such as new theatrical performances or show cancellations. It does not support navigation in the VE, but in the abstract space of the database of forthcoming performances. Another agent provides personalised assistance for the naive search of the interesting places in the VE when user looks disoriented, "walks in circles" or misses parts of the environment. The advice is based on an assessment of the users changes of position and movement history. The third agent uses natural language dialogue to find existing locations in the theatre.

The work carried out by Dijk and his colleagues (2003) presents an adaptive VE under development. It focuses primarily on developing personal agents for assisting navigation in a VE, raising in particular issues regarding their design criteria. The second agent is the most relevant for this review. It seems able to identify user's disorientation, but not enough information is provided with respect to this. Apart from a sample of behaviours which suggest disorientation, there is no correlation with any kind of performance indicators or with any other ways of extracting information that can support that indeed such behaviours reflect disorientation. In addition, an adaptive system should be able to automatically recognise the user as being disoriented. No information is provided about possible clustering techniques which could automatically identify the particular behaviours indicating disorientation. With respect to this type of behaviours, the significant aspects related to user model are surprisingly neglected. The adaptivity consists mainly in providing a navigational aid, (i.e. map on request), possibly enriched by landmarks and space partitioning. However, it does not involve any aspects regarding training efficient navigational rules or strategies.

Satalich (1995) investigated whether the tools supporting navigation awareness, that is the acquisition of complete navigational knowledge of a real environment, can be applied for supporting spatial awareness in VEs. This study involved a comparison between the map-supported human spatial behaviour in a real environment, and the behaviours exhibited in a virtual replica of that environment. In the testing phase, participants were asked to perform spatial tasks in the same VE. Findings indicated that the exposure to VE diminished or did not change the performance achieved by the experimental group whose navigation in physical world was supported by map. It seems that the novelty of VR technology could play an important role in the performance equation. One way to overcome this problem involves increasing the duration of users' exposure to VE.

3.3.4 Designing Guidelines for Supporting Navigation in VEs

This section introduces a critical review of the various guidelines for supporting navigation in VEs which have been proposed in the last decade. As mentioned in Section 2.6.2, users often encountered difficulties when navigating in unfamiliar physical places, and in particular, in unfamiliar VEs (Waller, 2000; Dijk et al., 2003). The computational complexity characterising VEs imposes several limitations on the level of detail provided by the VEs (Ruddle et al., 1997), reflecting on the limited sensorial stimulations. Such limitations are even stronger in the case of desktop VEs, given the restricted view field (Waller et al., 1998), absence of peripheral vision (Ruddle et al., 1997), difficulties of depth perception, restricted kinaesthetic (Waller et al., 1998) and proprioceptive inputs (Ruddle et al., 1997). These difficulties of navigating in unfamiliar VEs suggest the need to support navigation in VEs (Vinson, 1999).

Despite the outlined differences, there are outstanding similarities in the way in which people navigate in real and virtual world (Vinson, 1999), in particular in terms of acquiring spatial knowledge in VEs and in the real world (Ruddle et al., 1997), and of transfer of spatial knowledge from VE to the corresponding physical environment (Darken and Banker, 1998).

It has been hypothesised that understanding human navigation is beneficial for understanding how to build effective VEs for supporting navigation (Bowman, 1999). Despite its significance, "the support for effective navigation in VEs is often overlooked in the design process" (Darken and Sibert, 1996a). Designers of VEs are overwhelmed with the hardware and software aspects of the design, at the expense of not paying enough attention to user mental model of interacting with the system (Grant, 1990). In addition, the lack of a completely verified theory of the process of acquisition and use of spatial mental representations prevents us from giving easy *recipes* to the designers of VEs. As Satalich's (1995) results have suggested, the search for proper tools to support navigation and, most importantly, for ways to use these tools, requires considerable attention, since "any tool that attracts attention to itself may interfere with the learning it is supposed to facilitate".

An important input in designing VEs able to successfully accommodate navigation has come from fields like environmental psychology or architectural design (Lynch, 1960; Raubal and Worboys, 1999; Darken and Sibert, 1996a). Vinson (1999) argues for using the findings of research on real world navigation to generate guidelines for supporting navigation in VEs. On the other hand, architectural design and urban planning have investigated the relationship between people and their environment, and they have much to give on learning "how to construct space in a meaningful way in which people can comprehend and operate effectively" (Darken and Peterson, 2002). Seminal in this sense is Lynch's (1960) work on human understanding of urban place layout (Section 3.2.3). In fact, his principles for city design are regarded as the foundation for human wayfinding research (Strohecker et al., 1998; Raubal and Worboys, 1999; Darken and Sibert, 1996a; Darken and Peterson, 2002).

Darken and Sibert's findings (1996a) suggested that the principles of environmental design can be effectively employed in designing VEs supporting navigation. They highlighted the importance of the organisational structure of the environment, and of the presentation of maps. Later, Darken and Peterson (2002) identified a set of principles for the design of navigable VEs. Given the complexity of navigational tasks, depending on both internal representations and external environment, such guidelines offer only a generic framework whose applicability to concrete designing problems should be carefully considered. Such an adaptation of designing guidelines is particularly concerned with providing the proper amount of spatial information to address users' needs. Darken and Peterson (2002) discussed several navigational tools and mediators aimed to support the design of navigable VEs:

- *Maps.* Map orientation should match the task requirements, such as forward-up map for egocentric tasks and north-up map for geocentric tasks. The level of spatial abilities and in particular the mental rotation impacts significantly on the level of orientation which can be addressed by the map usage.
- *Landmarks.* Landmarks should provide both position and orientation information through their salient features. Enabling the users to personalise the spatial cues with additional information could prove useful when it is performed in a controlled manner.

  The role of landmarks in supporting navigation cannot be overemphasised. A VE containing well designed landmarks enables acquisition and application of spatial knowledge. Vinson (1999) identified a set of guidelines for landmark design in VEs, inspired from the substantial research on human navigation in real world.

1. It is essential that the VE contain several landmarks.
2. All five types of spatial cues should be included in the VE: path, edge, district, node, landmark.
3. Landmarks should have distinctive features like: significant height, complex shape, bright exterior, and large, visible signs.
4. Landmarks should be represented by concrete objects, rather than abstract ones.
5. Landmarks should be visible at all navigable scales.
6. A landmark must be easy to distinguish from nearby objects and other landmarks.
7. The sides of a landmark must differ from each other.
8. Landmark distinctiveness can be increased by placing other objects nearby.
9. Landmarks must carry a common element to distinguish them, as a group, from data objects.
10. Landmarks should be placed on major paths and at path junctions.
11. Paths and edges should be arranged to form a grid.
12. Landmarks main axes should be aligned with the path/edge grids main axes.
13. Each landmarks main axes should be aligned with those of the other landmarks.

- *Trails or footprints.* Trails of user's trajectory could be useful for search tasks. However, they present the risk of cluttering the space.
- *Tools for direction finding.* Directional cues are efficient when combined with directional landmarks, since both positional and directional information are linked together.

Guidelines for organising spaces for navigability are rooted in the fact that people usually dislike a lack of structure:

- *Implicit sectioning.* The structure underlying the organisation of an environment should be transparent to its users and consistent. Violations of this "organisational principle" should be even more transparent and clearly justified in order to prevent users from building a distorted spatial representation. Landmarks can be used to "reinforce the shape of the space". The elements of urban design can be provided through: useful paths, noticeable edges, meaningful landmarks. Complex spaces can be hierarchical divided into a number of small parts that are organised according to a simple organisational principle (Darken et al., 1998).

- *Explicit sectioning.* When the implicit organisation is not suitable for a particular environment because of the paucity of the objects to organise the space (e.g. ocean environment), an explicit sectioning can be employed.

Navigational tools and mediators summarised by Darken and Peterson (2002) represent the most comprehensive list of guidelines elaborated so far for supporting design of navigable VEs. Other attempts are those of Weisman (1981) who identified four designing aspects that could impact on spatial behaviour within VEs: visual access, architectural differentiation, signs and room numbers to provide identification or directional information, and plan configuration (Raubal and Worboys, 1999).

Chen and Stanney (1999) proposed a theoretical model of wayfinding which can be used to guide the design for supporting navigation in VEs. The authors identified five categories of navigational tools, according to their functionalities:

- tools displaying individual's current position,
- tools displaying individual's current orientation,
- tools recording individual's movement path,
- tools demonstrating the surrounding environment, and
- tools for guided navigational systems.

The suggestion for presenting the most appropriate type of aid to users depending on their goals is a strength of this model. Previously outlined guidelines for designing VEs, able to successfully support navigation, hold a high *face validity*[1]. Much research has been concerned with manipulating the technical aspects of VEs design, and in particular the additional navigational cues suggested by the above guidelines (Waller et al., 1998; Darken and Banker, 1998) (see Section 3.3.3). Such a line of research could greatly benefit from the insights into the psychology of individual differences, which surprisingly, have been exploited by very few studies in the field (Waller, 2000; Waller et al., 2001).

3.4 Discussion

There have been two directions of research focused on designing VEs for navigation support. One direction is concerned with manipulating technological factors characterising VEs. The studies outlined above try to address the issue of training for navigation by manipulating mainly the navigational cues within VEs. Such tools, among which the map is the most common, are easy to place on a VE and they seem to impact significantly on the quality of the acquired spatial knowledge (Darken and Sibert, 1996a). However this approach to training navigation has several limitations:

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[1] Face validity determines the suitability of a given measure for measuring a given construct, using common-sense criteria or intuition. It is a highly subjective judgment which offers weak evidence which however, does not imply that it is wrong (Trochim, 2000).

- In all these studies, the navigational tools are applied equally to each end user, without any attempts to tailor their design to user profiles. Such user profiles could be grounded on individual differences impacting on navigation, or in user mental models of navigation. This is the gap that this thesis is trying to address by focusing on individual differences in spatial behaviour which actually reflect different navigational rules or strategies.
- Some of these studies are primarily concerned with manipulating media for delivering training for navigation and comparing the efficiency of VE against paper or video tutorials. Despite delivering different navigational tools, there seems to be an emphasis on format rather than on the informational content of the tutorial. However, tutorial format should not come first, at the expense of content. The informational content is more difficult to address since it requires a thorough examination of user's strategies and procedures, a line of research not often pursued nowadays.
- The benefit of employing navigational cues is limited only to knowledge transfer but not to skill transfer from the virtual to the real world. Such studies are primarily concerned with transfer of knowledge from the VE, a computer generated world of a real environment, to its physical counterpart.

  This thesis focuses on identifying and training the efficient rules and strategies whose possible transfer to new VEs or real world in general is intended, rather than on the acquisition of the properties of the VE spatial layout for transfer in its real counterpart environment. Therefore, the training is meant to address a more complex set of knowledge and skills rather than those limited only to the spatial layout. The training is supposed to be formative rather than informative, with an emphasis on the efficient strategies or rules employed by the users.
- There is a gap between the existing models of navigation or acquisition of spatial knowledge and the manner in which VEs are designed. When it comes to navigation assistance this gap is even larger, particularly because these models of navigation contain few low-level details, such as rules, procedures or strategies. This aspect triggers the difficulty to implement those models into the design of VE, and therefore few serious attempts have been made in this direction. Today the only psychologically inspired adaptation of a VE design, through Lynch's theory (Lynch, 1960) is the one carried out by Darken and Sibert (1996a).

The other direction which has received considerably less attention focuses on human factors impacting on spatial performance. This is regrettable, since human factors seem to account for a much larger variance in spatial task performance (Waller, 2000). Given the paucity of such studies and the significant impact of individual differences, this latter direction is the one to which this thesis adheres. Apart from gender and computer experience, the individual differences in navigation are also investigated, through the user model of navigation. The idea is that efficient navigators develop qualitatively different navigation models, as compared to inefficient navigators. These models consist of interrelated navigational rules and strategies. Such rules would not only provide valuable insights in the understanding of navigation as a complex cognitive process, but would foster a qualitatively different approach in designing VEs for navigation assistance.

3.5 Summary

This chapter provides a critical review of the current models of navigation, together with an outline of the individual differences which impact on navigation within VEs. The difficulties encountered while navigating - one of the most common tasks in VEs - are to a large extent due to the poor design of VE. Such a design emphasises technological factors but fails to address sufficiently the human factors, which have been shown to account for a much larger variance in spatial task performance. Several individual differences, such as gender, computer experience, and spatial skills have been identified as impacting significantly on spatial performance. However, a large percent of the variation in spatial task performance is still unexplained. Searching for additional individual differences which might account for this unexplained variance, and benefiting from additional insights into the study of individual differences in navigating in hypertext, I conjecture that different spatial behaviours expressed in particular movement patterns could offer a possible answer. Navigational rules or strategies embedded in movement paths offer such answers and their identification and extraction is thoroughly presented in Chapters 8 and 9.

The apparent gap between the theoretical models of navigation and the design of VEs resides in the limited interest in user model, and insufficient accommodation of individual differences which impact on navigation. This gap impedes the proper exploitation of current navigational models and theories of spatial cognition. This thesis addresses this deficiency in the research literature. Therefore, consideration has been given to navigational patterns or rules which might impact on spatial task performance. The following two methodological chapters describe in detail the study methodology which enable the collection and analysis of the study data.

Chapter 4

Sense of Presence

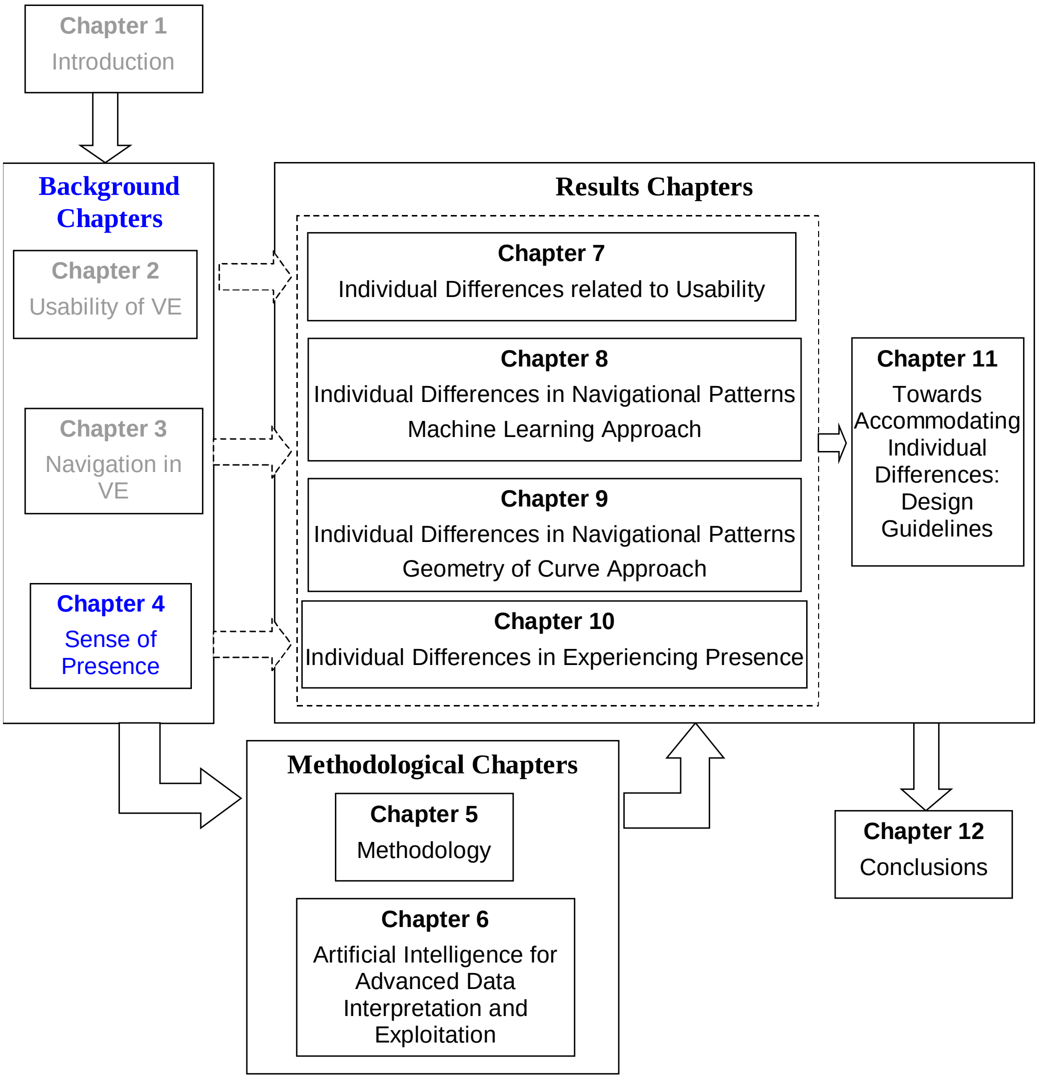

Figure 4.1: Road Map

4.1 Introduction

Virtual reality is an event or entity
that is real in effect but not in fact.
(Michael Heim, 1993)

Sense of presence is one of the most interesting phenomena which enrich users' experience of interacting with any type of system. It allows the users to *be there* (Schloerb and Sheridan, 1995), and moreover to perceive the virtual world as another world in which they really exist. The inner nature of this phenomenon poses a series of serious problems for investigating presence, at both theoretical and empirical level. The highly subjective nature of presence continues to challenge researchers for finding appropriate methodologies and instruments of measuring it. This is reflected in the ongoing theoretical work of conceptualising sense of presence. The difficulties relating to investigating presence led to a large set of definitions and measuring tools. Despite the diversity characterising this set, there is a common ground shared by researchers in the presence field which refers to presence determinants. Given the emphasis on technological factors, human factors impacting on presence has received considerably less attention. The attempt to address this gap, both theoretically and empirically represents one of the significant contributions of this thesis.

This chapter introduces the concept of presence through reviewing presence definitions and presence theories. The factors impacting on presence are broadly categorised into two groups, namely technological and human factors. The measurement methods and instruments developed for assessing presence are subsequently described. Given its significance in the context of system usability, a brief consideration is given to the relationship existing between presence and task performance.

4.1.1 Construction of the world

Understanding and representing the external world involves a long-time running process, which requires constructs and functions achievable through both genetic inheritance and educational environment. The manner in which one perceives and understands the world is determined by the way in which the world was previously internalised and its representation consequently created.

Within virtual realities, people exercise already acquired cognitive functions in order to build mental representations, this time of the virtual world. Within such a *metaphysical testbed*, Lauria (1997) identified virtual reality with, individuals construct its representation and plunge into in order to explore its understanding.

Presence can be approached through various philosophical positions grounded on the long-standing opposition of matter versus mind (Dreyfus, 2000). The treatment of these approaches goes beyond the topic of this thesis. However, to suggest the richness of theories which can be employed to describe the theoretical framework for presence, couple of these perspectives are briefly mentioned below.

Revonsuo (1996) considered immersion and sense of presence as “basic features of the high level structure of conscious experience”. The paradox of out-of-the-brain experience, consisting in the fact that the brain creates the experience of sense of presence within a world outside the brain, leads eventually to a natural virtual reality, namely “the sense of presence in and immersion into the world outside the brain”. Since conscious experience is an internal construction of the brain, the virtual reality metaphor could provide a significant testbed for investigating important aspects of consciousness.

In his book: *Being There: Putting Brain, Body and World Together Again*, Clark (1997) proposes body and world as controllers of embodied activity, which should be used in understanding the brain.

O’Regan and Noë (2001) offered a new approach of explaining the visual consciousness, or the subjective impression of seeing. They proposed vision as an exploratory activity, “instead of assuming that vision consists in the creation of an internal representation of the outside world whose activation somehow generates visual experience”. According to the authors, vision is seen as a mode of exploration of the world that is mediated by perceiver’s knowledge.

The need to understand the construction of world in the human’s mind, led to the emergence of different theories. Kelly’s (1955) personal construct theory is focused upon the analysis of the construct systems used by individuals in order to understand, structure and change their world. Anticipation and “man as scientist” are relevant ideas for the Kellyan theory. People anticipate events and experiences, build the reality, and test the constructs in day-to-day life. This will eventually trigger their validation as a criterion for keeping, adjusting or giving up constructs. Emphasising the role of assimilation and accommodation as functions applied to construct systems, Piaget (1954) used them to fill the gap from immediate experience to the mediated one.

Dealing with the same issue of mediation, Shapiro and McDonald (1993) proposed a dichotomy of the ways in which the reality is built. Information provided by the mediated representations or memories will take the form of reconstructed reality, while the filter applied to this information in terms of grasping the essence of its realism would lead to the constructed reality. The constructed reality is governed by the degree of accepting that the primary content of consciousness is real.

4.1.2 Mediation

Each new way of communication and particularly, tele-technologies provide access to more information. Besides the positive issues concerning quantitative aspects of the information achievable through these technologies, the quality of this information could be questioned. The increased amount of doubts regarding the authenticity and reliability of tele-technologies pushes us to reconsider the role of mediation. In other words, the new ways of communication raise epistemological questions or “are resurrecting Descartes’ doubts” (Dreyfus, 2000) and reintroduce the idea that our knowledge is indirect and mediated by even our sense organs. Teleepistemology, a term coined by

Golberg (2000) refers to the study of knowledge acquired at distance, through technical mediation or so-called *second degree mediation*.

Emphasising the meaning of mediation, a new concept, called telepresence has been introduced. Even though the idea of telepresence was anticipated by Robert Heinlein (1950) in his novel *Waldo*, the term was coined by Marvin Minsky (1980) and denotes a sense of being physically present at a remote world which is mediated by the system interface. This concept precedes and is closely related to the presence construct.

4.2 Sense of Presence

4.2.1 Defining Presence

One of the most common psychological phenomena experienced by users while they interact with virtual reality systems, is a sense of presence. However, a sense of presence can be experienced not only when people interact with virtual reality, but also during the use of any other media. Biocca (1997) argues that presence, as one of the VR goals,

> is part of an ancient desire for transportation and the experience of "physical transcendence" over the space we live in and to experience an *essential copy* of some distant place, a past experience, or the experience of another person.

In a widely accepted assertion, Sheridan (1992) and Schloerb and Sheridan (1995) described presence as a sense of being physically present at the remote site. Loomis (1992) pointed out that presence is a basic state of consciousness, consisting of the attribution of sensation to some distal stimuli, or more broadly to some environment. Slater and Usoh (1993b) described presence as "suspension of disbelief" experienced by users while being in a remote world and not the physical one.

Lombard (2002) also considered the first and the second order mediation applicable to the study of presence, where the second one relies beyond the human senses, on technology. Underlining the failure of mediation awareness, Lombard and Ditton (1997) conceptually delimited presence as "the perceptual illusion of non-mediation".

Building upon the aforementioned presence definitions, I was interested in identifying, according with traditional definition theory, their *genus* and *differentia*. These Latin terms have been derived from Aristotle's logic in order to define a concept by indicating its general kind of things to which it refers: the genus, and specifying the special features which set them apart from other things of the same kind. Thus, the concepts used for delineating the genus were *state of consciousness* (Loomis, 1992), *psychological state* (Lombard, 2002), *subjective experience* (Heeter, 1992), *subjective perception* (Lombard, 2000), *sense* (Minsky, 1980; Sheridan, 1992) and *illusion* (Lombard and Ditton, 1997).

Considering presence merely as a sense is, in my opinion, unnecessarily restrictive. At the same time however, the state of consciousness enlarges the boundaries of the genus needlessly, since everything that occurs in the *internal world*, the subjective world of inner thoughts (Jung, 1971), represents states of consciousness. While a quite large array of terms delineating genus have been identified, the distinguishing features, which are supposed to differentiate sense of presence from other psychological phenomena are clearer. The unanimously accepted construct of *being there* is the core aspect of presence, which occurs within one's consciousness. It is related to a shift of focus of consciousness (Lauria, 2000) from the local environment to a remote one, a shift which occurs insidiously.

In seeking a closer juxtaposition to the theoretical framework underlying it, presence is defined as follows (Sas and O'Hare, 2001, 2003):

> Presence is a psychological phenomenon, through which one's cognitive processes are oriented towards another world, either technologically mediated or imaginary, to such an extent that he or she experiences mentally the state of being (there), similar to one in the physical reality, together with an imperceptible shifting of focus of consciousness to the proximal stimulus located in that other world.

A conceptual delimitation should be made at this point. Despite of being often taken as synonyms, there is however a subtle difference between presence and *telepresence*, rooted in the proximity to the site where one perceives, acts and ultimately experiences presence. Draper et al. (1998) defined telepresence as "the perception of presence within a physically remote or simulated site".

A better understanding of presence can be obtained by identifying the potential factors whose influence can impact on presence. Apart from its theoretical contribution, such an understanding has valuable practical potential. It provides a set of factors whose manipulation could help VEs designers to size user's experience of presence.

4.3 Determinants of Presence

The factors affecting presence can be grouped into technological factors which consider the system and its characteristics, and human factors referring to users' cognitive and personality aspects (Lombard and Ditton, 1997; Lessiter et al., 2000). Since an entire set of studies have investigated the impact of technological factors, they are only briefly described in the following section. In contrast, the presence literature shows a lack of theoretical and empirical studies with respect to the impact of human factors on presence. One of the objectives of this research will be to focus on individual differences in experiencing presence.

4.3.1 Technological Factors

A large amount of work has been carried out in the area of technological factors affecting presence. Lombard and Ditton (1997) provided a detailed account of this. Some of these factors are: visual display characteristics such as image quality, image size, viewing distance, visual angle, motion, colour, dimensionality, camera techniques; aural presentation characteristics like frequency range, dynamic range, signal to noise ratio, high quality audio and dimensionality such as 3D sound. As stimuli for other senses, Lombard and Ditton (1997) referred to olfactory output, body movement, tactile stimuli, and force feedback.

Media and user characteristics were often mentioned as carrying a particular impact upon the level of sense of presence experienced by the users. However, there is little empirical research supporting this.

4.3.2 Human Factors

Psotka and Davison (1993) considered two categories of factors determinant of immersion, such as susceptibility to immersion and quality of immersion. The first set refers to human factors with an emphasis on cognitive aspects such as imagination, vivid imagery, concentration, attention and self-control, while the second set is primarily concerned with technological factors like affordances of Virtual Reality (VR), distractions from the real world or physiological effects.

Kaber, Draper and Usher (2002) noted that the personality traits discussed in the VR literature seem to be predominantly mentioned in the context of presence experienced within the VE. These factors were primarily referred to as immersive tendencies and attention. They cover an entire set of users' characteristics such as suggestibility of immersion, tendency to daydream, becoming lost in novels, concentration and robustness to distracting events. As the following subsections depict, empathy, absorption, creative imagination, cognitive style and willingness to be transported into the virtual world specifically consider these issues. Further information regarding the description of scales employed for measuring them are detailed in Section 5.6.3, while the results are thoroughly described in Sections 10.2, 10.3 and 10.4.

Empathy

Empathy is probably the most frequently mentioned cognitive aspect which might affect presence (Lombard, 2003). Lombard and Ditton (1997) suggested that intensity and polarity of emotions experienced by users during mediated activities could significantly impact on presence, even though no empirical study had yet indicated it.

Davis (1994) identified empathy with a set of constructs associated with the responses of individual to the experience of another. It involves the ability to engage in the cognitive process by adopting another's psychological point of view, together with the capacity to experience affective reactions to the observed experience of others. In order to develop such capacities and exhibit empathic behaviour, one should be able to assume perceptual, cognitive and affective roles. Among the empathy constructs identified by Davis (1994), within this thesis, the *Fantasy Subscale* received the greatest attention, because it resembles a prerequisite for experiencing presence: the ability to imaginatively transpose oneself into fictional situations. Fantasy Subscale is a cognitive factor which involves imagination for experiencing feelings, thoughts or actions of characters in creative works. For a detailed description of this scale, see Section 5.6.3.

A theoretical perspective in the psychology of hypnosis could support the study of presence. To date I have only identified the work of Tromp (1995), where the hypnosis results were theoretically exploited in the investigation of presence.

Hypnosis is a state of consciousness characterised by increased suggestibility, enhanced imagery, disinclination to plan and reduction in reality testing (Hilgard, 1979). An important fact about hypnosis is related to the individual differences in response to suggestion. Absorption and creative imagination are the most important personality correlate of hypnotisability (Hilgard, 1979). The following two subsections introduce these two constructs.

Absorption

Lombard and Ditton (1997) suggested absorption as another possible factor which influences presence. They mentioned Quarrick's (1989) work, who indicated that during absorption, sense of self and time fades as the person merges with a fascinating stimulus.

The absorption construct elaborated by Tellegen (1981, p. 222) is defined as a state of "openness to experiencing, in the sense of readiness to undergo whatever experiential events, sensory or imaginal, that may occur, with a tendency to dwell on, rather than go beyond, the experiences themselves and the objects they represent". For an elaborated presentation of the scale designed by Tellegen (1982) to measure this construct, see Section 5.6.3.

Absorption "is a total attention, involving a full commitment of available perceptual, motoric, imaginative and ideational resources to a unified representation of the attentional object" (Tellegen and Atkinson, 1974, p. 274). Furthermore, the main features of the absorption construct are outlined, as Tellegen and Atkinson (1974) identified them.

1. A heightened sense of reality of the attentional object. The object, either perceived or imagined, grasped in one's attentional focus is experienced as present and real. The authors assumed that an already engaged representation of the focal object is incompatible with any other reflective consciousness about this primary consciousness content. When this state is not reached, the person becomes aware that *this is only in one's mind* which seriously prevents the suspension of disbelief.
2. An altered sense of reality in general and of self in particular. Absorbed attention focuses on some facets of reality, emphasising to a greater extent the experience regarding them, and limiting the awareness of other facets.
3. Imperviousness to normally distracting events. Once an object becomes the focal object, it completely holds the attentional resources, such that it is perceived entirely, in all its details while the individual becomes less distracted by the collateral external events.
4. Cognitive aspects: empathy and cognitive style. Tellegen and Atkinson (1974) considered that absorption is related to empathy and a distinctive cognitive style.

5. The motivational-affective component. Motivational-affective component is the openness to experience willingness for a relationship with the object that enables involvement experience.

Each of the aspects characterising absorption places this construct within a conceptual framework closer to presence. Undivided attention towards the remote world (Witmer and Singer, 1998; Draper et al., 1998; Kim and Biocca, 1997), lack of awareness for unrelated issues (Kim and Biocca, 1997), impermeability to distractions from the physical environment (Kim and Biocca, 1997) are all aspects which enrich the experience of presence (Lombard and Ditton, 1997). The two cognitive aspects such as empathy and cognitive style, together with the motivational-affective component expressed in terms of openness to experience are considering at lying at the core of absorption. In addition, they hold high face validity which positions them at the core of presence as well. In fact, as shown in the following sections this position is also sustained by theoretical work in the field of presence.

Creative Imagination

In addition to empathy and absorption, within the presence literature imagination has also been considered as a potential factor impacting on presence (Heeter, 1992; Lauria, 1997). Imagination is the ability to generate mental representations of objects, persons or events not immediately presented to the senses (Singer, 2000).

Studies carried out in the area of hypnosis, indicated that creative imagination and absorption are partly overlapping concepts. Imaginativeness as a personality trait (Hilgard, 1979) was studied in relation with *openness to experience*, due to its association with daydreaming tendencies (Singer, 2000). The Creative Imagination Scale (CIS) (Barber and Wilson, 1979), a scale developed for measuring creative imagination and used in this thesis is introduced in Section 5.6.3.

Cognitive Style

Understanding users' preferred manner of processing information opens a door towards their perception of the world, either physical or virtual. The term of cognitive style was coined by Allport (1937) and is rooted in Jung's (1971) theory of psychological types.

Despite the large number of meanings attributed to it, cognitive style refers to enduring patterns of cognitive behaviour (Grigorenko, 2000). It describes the unique manner in which unconscious mental processes are used in approaching and/or accomplishing cognitive tasks.

Curry's Onion Model (1983), presented by Riding (1991) proposes a hierarchical structure of cognitive styles with:

- the outermost layer referring to the individual's choice of learning environment,
- the middle layer referring to the information processing style, and

- the innermost layer consisting of cognitive personality style.

Cognitive style was referred to in the presence literature as a possible significant issue affecting presence (Lombard and Ditton, 1997; Heeter, 1992). Unfortunately, without being supported by any empirical study, such statement cannot provide additional information about the particular level of cognitive style which might be considered (within Curry's (1983) Onion Model) or about the specific instruments for measuring it.

In order to address this problem the level of depth is considered in the context of this hierarchy. Defined as the individual's tendency to assimilate information, cognitive personality style represents the innermost layer. It is considered to be the most enduring and context-independent feature of style. Thus, it should make little difference if the context of providing cognitive stimulation is technologically mediated or not, as long as the given task involves information processing. To conclude, this level which is the least likely to change seems to represent a promising starting point whose examination could enrich our understanding into one's learning style (Cunningham-Atkins et al., 2003). Once such level is understood, the analysis can be continued with middle and outermost layers which represent direction of future work. Atkins et al. (Atkins et al., 2001) identified the following theories focusing on cognitive personality style:

- The Felder and Silverman's (1988) Learning Style Model provides the following five types: sensing/intuitive, visual/verbal, inductive/deductive, active/reflective, and sequential/global. There are some limitations of this model, mainly regarding the measuring instrument which is still under development.
- Based on the ability to extract details from a context, Witkin and Goodenough (1981) developed the well-known theory of field–dependence and field–independence. Field–dependent individuals process information in a global, holistic, and more passive manner, since their processing tends to be dominated by the existing organisation of the perceptual and cognitive field. Field–independent individuals process information more actively by imposing structure on the learning material. Identifying the relevant parts and analysing the interrelationships among those parts are strengths of field–independence (Goodenough, 1976). The validity of instruments used to measure field dependence–independence is questionable (Atkins et al., 2001).
- According to the manner of organising and representing information, Riding and Rayner (1998) considered two dimensions of cognitive style: wholist–analytic and verbal–imagery. Wholist–analytic dimension reflects the tendency to organise information in parts or as a whole, while verbal–imagery dimension addresses the way in which an individual would represent knowledge in words or mental pictures. In order to assess these two dimensions, the authors proposed the Cognitive Styles Analysis (CSA), based on a comprehensive review of different cognitive styles (Atkins et al., 2001).
- The Myers-Briggs Type Indicator (MBTI) (Myers and McCaulley, 1998) is based

on Carl Jung's (1971) theory of psychological types. Preferences in the four dimensions of: extraversion–introversion, sensing–intuition, thinking–feeling, and judging–perceiving, are used to characterise people according to sixteen types. This model provides an efficient measuring instruments, whose validity and reliability has been demonstrated. Despite the fact that the primary use of MBTI is in the area of personnel psychology, its application to learning style could provide a fruitful contribution.

Given the relative limitations regarding the measuring instruments developed within the first two models, and the stronger theoretical foundation of the last model compared with CSA model, is argued in this thesis that the last theory offers the best model to investigate the personality cognitive style and to explore the potential relationship between this construct and presence. This is also supported by the psychologically highly subjective nature of presence experience. Therefore a thorough analysis of presence from a personality perspective could help understanding those enduring aspects impacting on presence. Nevertheless, the findings obtained in this manner (see Section 10.4), could be further extended through investigating the relationship between presence and cognitive style, defined according to other models. The following section presents a detailed description of main dimensions of personality cognitive style, as highlighted by Jung (1971).

Jung's Psychological Types

The two basic types: extravert and introvert adapt themselves by means of four functions, which underline four other special types. The basic types, or so-called attitude-types are identified on the basis of their attitude to the object. While the extraverted type has a positive relationship with the object, whose value and significance is overestimated and overtly recognised, the introvert manifests little interest in objects, as if one fears that the objects would gain power over him/her. The function-types are thinking, feeling, sensing and intuition. The extraverted and introverted types based on these factor types, will be briefly contrasted.

The extraverted type is predominantly oriented towards the external world of objects, events or people, to such an extent that his/her entire behaviour could be explained and predicted based on this. The "objective happening" (Jung, 1971) captures his/her attentions and motivates his/her actions.

Extraverted thinking is grounded on the incoming information originated in the external world, rather than in the subjective one (e.g., discoveries are always grounded on empirical evidences). In a similar manner, the outcomes of the extraverted thinking are directed outwards. Extraverted feeling is also under the influence of objective happening, in terms that the individual surrounds himself/herself to the influence of the object. This can lead to an unquestionable acceptance of the objective values, as long as these values are traditional or generally accepted. Extraverted sensitive is oriented by the external world, but in this case the objects are valued for their quality to excite emotions. Since the realism is highly appraised, the source of sensation should be concrete and real. Extraverted intuitive is directed to the external objects, and is able to understand relations about things, often through the insights. The extraverted intuition strives to envisage the widest range of possibilities. On these grounds, facts are acknowledged only if they open new possibilities of advancing beyond them.

The introverted type is oriented by the subjective, internal data. Significant for an introvert is how he/she perceives the world, rather than how the world really is. Jung (1971) considered the inborn psychic structure, rooted in the collective unconscious as determinant in directing the introvert attitude.

The introverted thinking is determined by subjective factors: it is originated in the outer world, but it ends in the inner world of thoughts. The main concern consists of grasping new views rather than knowledge of new facts. This type formulates questions and creates theories, and sees facts only as evidence for the theory and nothing more. The introverted feeling type is determined by the subjective factors. While the extraverted type strives to subordinate himself/herself to the object, the introvert strives to subordinate the object. The introvert feelings are more intensive than extensive. For an introvert, sensation is based on the subjective component of perception, in terms that he/she will always find in the object something which does not exist or is merely suggested by it. Accordingly, the introvert sensate will grasp more than just the superficial level of the physical world, because he/she seeks for the unconscious image which will match the reality, as a "psychic-mirror world". The unconscious image is chosen on the basis of the intensity of the subjective sensation excited by the real stimuli. In a similar way, introverted intuition is directed to the inner objects related to the content of the collective unconscious.

Willingness to Experience Presence

Among the other individual differences which might influence presence, I considered in addition the *willingness to experience presence* or openness towards being "transported there", into the remote world. This factor is characterised by both cognitive and emotional components and its role can be better understood if one looks at it as a prerequisite for *willingness to suspend disbelief.* Willingness to suspend disbelief that the determinants of user's experience are not real was often mentioned in relation to sense of presence. It seems to be a necessary condition for experiencing a high level of sense of presence (Laurel, 1993; Slater and Usoh, 1993b) and ultimately enjoying a mediated experience of any kind (e.g., theatre, literature, television, film, VR).

Lombard and Ditton (1997) considered willingness to suspend disbelief as a variable likely to induce presence, through weakening the awareness of the mediated experience. Users able to cease considering that the mediated world is a fake and more willing to accept it as real, feel a heightened sense of presence. Central to this concept is *engagement*, which Laurel (1993) described as a primarily emotional state with cognitive components.

Each of the factors previously described: empathy, absorption, creative imagination, cognitive style and willingness to experience presence have been often referred as carrying a potential impact on presence (Heeter, 1992; Lauria, 1997; Lombard, 2003; Lombard and Ditton, 1997). Without covering exhaustively the list of human factors impacting on presence, these factors constitute nevertheless a core. As presented in Section 10.3 three of these factors account for 45% of the variance in presence. Given the lack of empirical study in this particular area, this work represents a beginning. Concentrated attention, suggestibility, critical thinking or sensation seeking are other factors which could impact on presence. Other human factors to be considered as potentially contributing to an increased level of presence are those related to specific skills in the context of particular tasks, i.e. spatial abilities for spatial tasks. Such skills could lead to better performance and arguably to increased presence.

The following section introduces the theoretical approaches employed for explaining presence, as summarised in the taxonomy of telepresence theories developed by Draper et al. (1998).

4.3.3 Presence Theories

Several presence theories have been developed in the attempt to extend the understanding of presence. Draper (1998) identified a first group consisting of psychological models of presence and a second one consisting of technological models of presence.

Psychological Approaches to Telepresence

Telepresence as *Flow* Experience This theory states that people enter into a flow state, when they are completely absorbed in activity, during which they lose their sense of time and have feelings of great satisfaction. It is supposed that people should be actively involved in a difficult task that puts demands on their mental and/or physical abilities. Csikszentmihalyi (1990) defined *flow* as:

> a state in which attention is so concentrated on some tasks as to render one unconscious of stimuli outside of the task, including even awareness of self and the passage of time.

Attention described by this theory resembles outstandingly the attention component of the absorption construct (Tellegen and Atkinson, 1974). The role of absorption in increasing presence has been theoretically harnessed in previous section and empirically suggested in Chapter 10.

Behavioural Cybernetics The core of this approach is that during goal-directed actions, humans respond to information present in the environment by manipulating the information or the environment (Smith and Smith, 1985). This theory examines the impact of proximate versus distal access. Two aspects are relevant in this respect:

feedback and feed-forward. While feedback refers to individuals' answers to the information present in the environment, feed-forward refers mainly to manipulating the environment. Since one of user's goals of interacting with the system is controlling the feedback, problems can occur if in the chain of feed-forwards and feedbacks, individuals' expectations are not met (i.e. temporal or spatial delay).

This theory implies an evolution of user and environment, tied in a cycle of reciprocal effects of one on the other. When the environment changes, the user changes himself/herself, which in turn changes the environment. It emphasises the importance of action, in terms that the more cognitive resources are required the higher the likelihood that the user would experience presence.

Structured Attentional Resource Model for Teleoperation The strength of this theoretical model consists in its capacity to explain the incidence of telepresence and the failure to observe a relationship between telepresence and performance (Schloerb and Sheridan, 1995).

In order to accomplish difficult tasks, humans need to concentrate attentional resources. The perceptual systems can be divided into attentive and alerting components. The attentive perceptual system is devoted to looking for and interpreting task-related information. After this, the attentive perceptual system develops response strategies for a better adjustment to the environment. During this complex activity, attention is still paid to the information not directly related to the task, but which can become relevant for the current activity. Usually, such kind of information act as distracters, perceived by the alerting perceptual system. Once they become relevant for the task, they become the objects of the attentive perceptual system. In this context, the telepresence can be considered as a state achieved from commitment of attentional resources to the remote environment. The more resources a user devotes to processing information from the remote environment, the stronger the sense of presence.

Telepresence reflects the degree to which attentional resources are involved in processing the perceptual inputs from the remote environment, and in formulating responses to them. Since the presence of distracters could impede the performance of the task being carried out, one should be able to change one's attentional focus between the remote environment and the local one. In this way, they will discriminate the task-relevant information.

According to this theory, the more complex and demanding the task, the more attentional resources will be activated and consequently, the stronger sense of presence. In order to allow the user to experience a higher degree of presence, the designed tasks should be interesting but made gradually difficult, be well structured and directly linked with the final goal of the activity. All these factors maintain a high level of interest, facilitating the concentration of attention.

Almost all presence theories refer to attention as a significant issue underlying presence. Witmer and Singer (1998) suggested that focusing one's attention on a meaningful stimuli set supports one's sense of presence. Emphasising the role of attention, Draper et al. (1998) proposed an integrative approach to telepresence, featuring a structured attentional resource model. Kim and Biocca (1997) stressed the role of attention in each of physical, mediated (VE) or imaginal space (of daydreams and dreams), where the user could experience presence.

Technological Approaches to Telepresence

Sheridan's Telepresence Model According to Sheridan (1992), the user seems to lose the awareness of being in the local environment, gaining instead a feeling of being in the remote environment. He defined telepresence as a *subjective sensation* triggered by a *compelling illusion* of mediation.

According to Sheridan (1992), the sense of presence can be induced by five variables. Three of them are technological, such as the extent of sensory information (their fidelity and richness), the control of sensors relative to environment, and the ability to modify the physical environment (Figure 4.2). The others two are task/context-based, such as task difficulty and degree of automation.

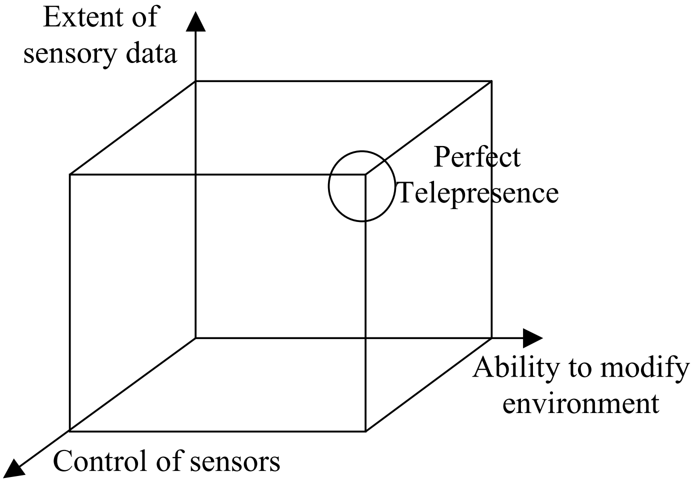

Figure 4.2: Sheridan's Determinants of Presence

This theory stresses the importance of both the richness of sensory information and the amount of control the user has on the remote environment. Unfortunately, the author does not describe precisely the magnitude in which each of these factors affect both the telepresence or the performance, and the relationships between these two latter constructs.

Steuer's Telepresence Model Steuer's theory (1992) defines presence as a "sense of being in an environment" and identifies two technological dimensions of it: vividness and interactivity. Vividness refers to "the ability of a technology to produce a sensorially rich mediate environment" and has two determinants, such as sensory breath and sensory depth. Interactivity refers to "the degree to which users of a medium can influence the form or content of the mediated environment". It is determined by the immediacy of response, the number of possibilities for action and the ability of the system to adapt itself naturally and predictably to the changes in the mediated environment.

This theory emphasis the significance of communication medium between the local and remote environment, in experiencing presence. It occurs when a user is involved in both these environments, but feels being more a part of the remote world.

Schloerb's Telepresence Model According to Schloerb's theory (1995), the telepresence occurs when the person perceives that is physically present in a remote environment. He distinguished between objective and subjective telepresence. Objective telepresence is not just related to performance but is defined as performance (the probability of successfully performing a remote task). This concept involves the ability to manipulate a remote environment. On the other hand, subjective telepresence is the likelihood that the performer considers himself/herself to be physically present in the remote environment. In this case, the user actually believes that he/she is operating within a remote environment.

According to this theory, the usefulness of objective telepresence, through which one can satisfactorily complete the required tasks is recognised. However, apart from this acknowledgement of the relationship between the objective telepresence and task performance, the usefulness of subjective telepresence is questioned.

Zeltzer's "AIP" Model For Zeltzer (1992), presence is "the sense of being in and of the world". He considers three features of graphic simulations such as: the degree to which the world is capable of simulating the interactions possible in a physical world, the capability for real time control, and the number or fidelity of the available sensory inputs/outputs. This theory highlights the connection between presence and the user's task and argues that the most important aspects of sensory input and output with respect to presence will be the ones most important to the task performed (Snow, 1996).

All these three components define the axes of the *AIP cube* (Figure 4.3), which states for autonomy, interaction and presence. The position of a certain system in this cube defines its type (e.g., a system occupying the location placed somewhere at the high end of each axis represents a virtual reality system).

This theory questions the presence–task performance relationship. Zeltzer seems less convinced of the benefits of the presence than many other authors, explaining that such kind of system can be very demanding.

Witmer and Singer's *Cognitive Factors* Witmer and Singer (1994) define presence as "the subjective experience of being in one place when one is physically in another one". They consider four factors that might impact on presence, such as control factors,

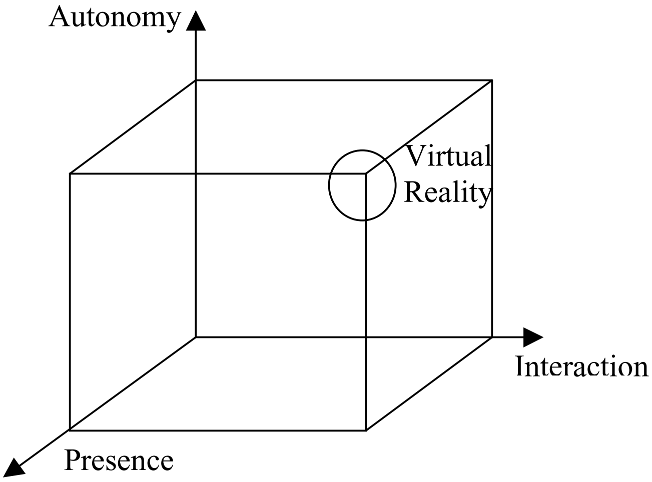

Figure 4.3: Zeltzer's AIP Cube

sensory factors, distraction factors and realism factors. Each of them can be subdivided in the following factors:

- Control factors include:
    - degree of control (to which it is possible to interact with the virtual world);
    - immediacy of control (to which user action and world reactions display appropriate continuity);
    - anticipation (ability to predict what will happen);
    - mode of control (the manner in which interactivity is provided);
    - physical environment modifiability (the degree to which objects in virtual world may be modified).
- Sensory factors include:
    - sensory modality;
    - environmental richness;
    - multi-modal presentation (more than one sensory modality);
    - consistency of multi-modal information (multi-modal presentations are mutually congruent);
    - degree of movement perception;
    - active search (control sensors to allow exploration of the world).
- Distraction factors include:
    - isolation (the degree to which the local stimuli are masked);
    - concentration of attention (the ability to ignore distractions);
    - interface awareness (the transparency of the human–machine interface).

- Realism factors include:
    - scene realism;
    - consistency of information with the objective world;
    - meaningfulness of the experience (motivation, experience, task importance).

This theory states that a direct relationship exists between presence and control/sensory factors. Sensory modality, which might be affected by a hierarchical relationship among the senses seems not to be involved in this relationship. Distraction and realism factors could determine feelings of separation anxiety or disorientation after the subjects end their interaction with the virtual world.

Slater and Usoh's *NLP Model* (Neurolinguistic programming) Slater and Usoh (1993b) defined presence as users' "belief that they are in a world other than where their real bodies are located". Presence is a state of consciousness, the (psychological) sense of being in the VE, and corresponding modes of behaviour (Slater et al., 1995). The authors found two sets of determinants for sense of presence:

- External factors which include:
    - display quality;
    - consistency of presentation;
    - ability to interact with the environment and of the environment to interact with the user;
    - anthropomorphism of the user's representation in the virtual world;
    - clarity of casual relationships between user's actions and reactions in the virtual world.
- Internal factors which include:
    - representation system related with the sensory mode of information and whether an image is external, remembered or constructed internally. Have been identified three key representation systems: visual, auditory and kinaesthetic;
    - perceptual position: first position (as an actor), second position (an observer of action), and third position (abstract point of view, as if not present at all).

According to this theory, presence is a state of consciousness, the psychological sense of being in the VE. It is also seen as a function of two orthogonal variables: the extent of the match between the display sensory data and the internal representation system, and on the other hand, the match between proprioception and sensory data (Slater et al., 1996).

Despite focusing on technological factors impacting on presence, this theory positions itself somewhat closer to those theories focusing on psychological approaches to presence.

It considers the effectiveness of presence as dependent on system versatility in supporting through different features, the different communication styles inherent to its users.

Discussion

These models of (tele)presence are organised along the two fundamental groups of factors which impact on presence, such as technological and human factors. However, there is an uneven development of these theories along the two dimensions, since technological factors seemed to receive greater attention from the research community. Distinct sets of factors have been identified within each group. There is a high degree of overlapping between the factors described by each model. However, once again the factors identified with respect to technological aspects of the system prevail over the factors referring to users' individual characteristics. This indicates a gap, which part of the work carried out within this thesis tries to address. The experiment carried for the purposes of this thesis involved a desktop VE system, whose deployment of technological factors is rather limited. This has been deliberately considered in the choice for the experimental testbed, in order to limit the impact of these factors and focus on the impact carried by human factors on the experience of presence (see Section 5.2 for a detailed description of the VE). The efforts invested in this line of research could be efficiently exploited for the development of hybrid theories, focusing simultaneously on both technological and human factors, and on the relationship between them, for providing a comprehensive explanation of presence.

The two groups of factors impacting on presence and taken as basis for grouping the presence theories should be seen on a continuum, rather than a dichotomy. Both human and technological factors should be seen as part of a wider equation whose addressing increases the potential of understanding and possible manipulating presence. A marriage between these two factors is a must for any attempt to build systems able to adapt themselves to user characteristics in order to control the level of presence (see Section 2.6).

The distinction between presence and immersion, often mentioned in presence literature imposes itself with respect to these two groups of factors. Immersion is usually associated with technological factors referring to the extent to which computer generated worlds are *extensive* (able to accommodate a large set of sensory systems), *surrounding* (able to provide information from any virtual direction), *inclusive* (able to shut out all information from physical world), *vivid* (able to provide rich information content, resolution and display quality) and *matching* (able to accurately reproduce the body movements previously tracked) (Slater et al., 1996, 1995). In contrast presence relates more to human factors, whose impact is unfortunately less explored.

Conceptualising presence is the initial stage of understanding this construct. It has been followed by the attempts of measuring presence. Different methods and measurement instruments have been proposed for offering quantitative indicators of the degree of presence that one can experience.

4.4 Measuring Presence

Despite its significance, measuring presence raises significant challenges, primarily related to the nature of presence. Presence is a psychological phenomenon, subjectively experienced inside the inner world of one's consciousness. Therefore, capturing and analysing it requires a certain degree of introspection, together with one's understanding of what presence means (or at least of what the experimenters think it means). Both these two aspects put additional demands on users, and if not completely met, they impede on the internal validity of presence measurements.

In addition, presence is a state or a transient psychological condition which is context-dependent, and which accordingly could vary within the same individual during an experiment. It is versatile, does not obey to *all or nothing* principle and its insidious nature makes presence difficult to grasp.

Therefore, participants could encounter difficulties in assessing their level of presence after the task has been completed and the experiment has ended. Even more difficult is measuring presence during the duration of experiment. This involves asking somebody to be permanently aware of each change occurring in his/her level of presence. Such a requirement adds itself to those involved in the execution of the task, inducing therefore cognitive overload. This could either prevent the subjects to experience presence or affect the task performance. Either case impacts on the measurement validity.

Another difficulty in measuring presence is related to the complexity and multi-dimensionality of this construct (Lombard, 2003). This is reflected in the different definitions and theories trying to explain presence. In addition, presence research seems to be an interdisciplinary field, which benefits from inputs from various disciplines such as psychology, philosophy, computer science, media studies, drama studies etc., to enumerate the most important ones. These multiple perspectives provide valuable insights into understanding presence, but at the same time they come at a cost. A fully articulated and commonly accepted theory of presence requires a *lingua franca* of presence. The efforts invested in this direction can lead to a common ground in understanding presence. However, beside this there are conflicting opinions regarding presence, which impact negatively on the attempts of measuring it.

Lombard (2003) identified two general approaches to measuring presence: *subjective measurements* and *objective measurements*. Subjective measures usually consist of self-rating questionnaires which require participants to evaluate the experienced level of presence. Some of the limitations of this approach have been introduced above. They are mainly related to the inner and versatile nature of presence, and to the level of introspection assumed that participants are able to achieve. Such kind of information could be elicited post experiment or during the experiment.

The main advantage of the subjective measures consists of their accessibility. They also come at low cost and very important, appear to be valid and reliable measures (Prothero et al., 1995b). As Lombard (2003) mentioned, "several presence questionnaire instruments that may be valid and reliable across different participant groups, experimental conditions, stimuli, and settings, have been or are currently in development". Such questionnaires have been developed by Lessiter et al. (Lessiter et al., 2000), Lombard (2000), Schubert (1999), Witmer (1998), Slater et al. (2000). For the purpose of this thesis, a presence questionnaire has been developed (see Section 5.6.2).

In order to overcome some of the limitations related to subjective measures of presence, another approach started to emerge. At the core of objective measures lies the hypothesis that, while the users experience presence, a series of physiological and behavioural modification occurred in their bodies. The particular physiological modifications considered as reflecting presence are skin conductance, blood pressure, heart rate, muscle tension, respiration, ocular response, posture etc. (Lombard, 2003).

These measures involve the recording of such modifications, in real time and present the considerable advantage of being unobtrusive. They can be also carried out without requiring subjects' involvement in these measurements. The objective measurements have their own limitations, such as high cost and difficulties in administrating them. However, their main drawback concerns the limited evidences of the fact that physiological modifications correlate with presence.

Another aspect of interest regarding presence is its relationship with task performance. The significance of this relationship justifies the efforts invested in defining and measuring presence. At the same time, this issue has generated serious theoretical treatments and empirical investigations.

4.5 Presence and Task Performance

The existence of a relationship between presence and task performance is arguable and has given rise to a long-standing debate in the presence research area. More empirical studies are required in order to refute/support this dependency and offer insights into its nature. Theoretical work and empirical studies have highlighted two possible research positions. The first position states that presence is merely an epiphenomenon (Ellis, 1996; Welch et al., 1996), and consequently its impact upon task performance is limited. According to this position, the role of presence consists only of affectively colouring the user's experience.

The second position argues that presence impacts on the performance of tasks carried out within the virtual environments. There are two perspectives on this position. The first, and probably the most important one argues for a causal relationship between presence and task performance (Sadowski and Stanney, 2002). This perspective has fuelled most of the research in the field. However, the issue of causal relationship presents a two-fold problem. Firstly, it is a challenge to design an experiment for highlighting the causal relationship, which would go beyond mere correlation and secondly this relationship, if it exists, would seem to be highly *task-dependent* (Stanney, 1995; Slater et al., 1996).

Tasks to be performed within VEs obey the same set of constraints which limit the range of actions available in VEs. Therefore, the main groups of VE tasks involve: navigation and locomotion; object selection; and object manipulation, modification or query (Esposito, 1996; Gabbard and Hix, 1997) (see Section 2.3). Given the frequency of the first set of tasks and the increased difficulties associated with their study in the real world (for a review see Section 2.3), navigational tasks have been considered at the core of this thesis. Typical navigational tasks are: exploration, search, distance estimation, direction estimation (Darken, 1995; Darken et al., 1998; Satalich, 1995; Snow, 1996).

The significance of the content being delivered through any mediated experience has been related to the nature of activity or tasks in which the user participates, which in turn seems to impact on presence (Lombard and Ditton, 1997). Heeter (1992) distinguished between two potential groups of tasks which could impact differently on presence, which are related to two fundamental types of activity: learning or playing. Particularly, in the case of tasks involving a ludic component, the sense of presence is likely correlated with enjoyment, which in turn is likely correlated with task performance (Barfield et al., 1995). Tasks or activities which involve ambiguous verbal and nonverbal social cues and sensitive personal information exploits better the medium's potential to offer presence than do simple nonpersonal tasks (Lombard and Ditton, 1997). Correlations between performance improvement and presence appear to be positive. However, they are usually weak since less than 10% of variance in the performance seems to be accounted for the perceived presence (Snow, 1996).

Despite this limitation, the causal relationship presence–task performance has increased face validity based on the perceptual and cognitive psychology of skills transfer (Stanney et al., 1998b). In this light, an additional benefit of understanding this relationship consists of the transfer of skills from the VE to the real world. Slater et al. (1996) considered presence merely as a facilitator whose main contribution consists of enabling the user to perform naturally, in a similar way one does in the real world, or in other words inducing one's "natural reactions".

The second possible explanation of this mysterious dependency between presence and task performance consists of viewing it as a mediated relationship. In other words, presence and task performance could be in fact related to a third extraneous variable or set of variables (Stanney et al., 1998b; Slater et al., 1996), which impact on both presence and task performance. These extraneous variables were considered to be related to the technological aspects of VEs, such as improved VEs (Stanney et al., 1998b) or immersion (Slater et al., 1996). It is my conjecture that they can be also related to users' characteristics or, in a larger framework, to both subjective factors and objective factors. Within this thesis, this relationship is investigated in this light of personality cognitive style (see Section 10.5).

4.6 Summary

This chapter introduced the presence construct and presented a thorough review of presence determinants and theories. Highlighting the uneven interest manifested in this research area, interest which favours *technological factors*, this thesis advocates a shift of interest which would motivate studies focusing primarily on *human factors*. The latter term refers to user characteristics, such as personality or cognitive factors rather than bodily-related aspects, and this working definition of human factors is the one used within this thesis. Despite the theoretical acknowledgement of their relevance, the impact of human factors on presence received little attention within empirical studies.

This chapter provides a basis for the experimental findings related to the individual differences in experiencing presence (see Chapter 10) and is the last of the background chapters. The following two chapters introduce the experimental design and familiarise the reader with the machine learning techniques and methods that have been used within this thesis.

Chapter 5

Methodology

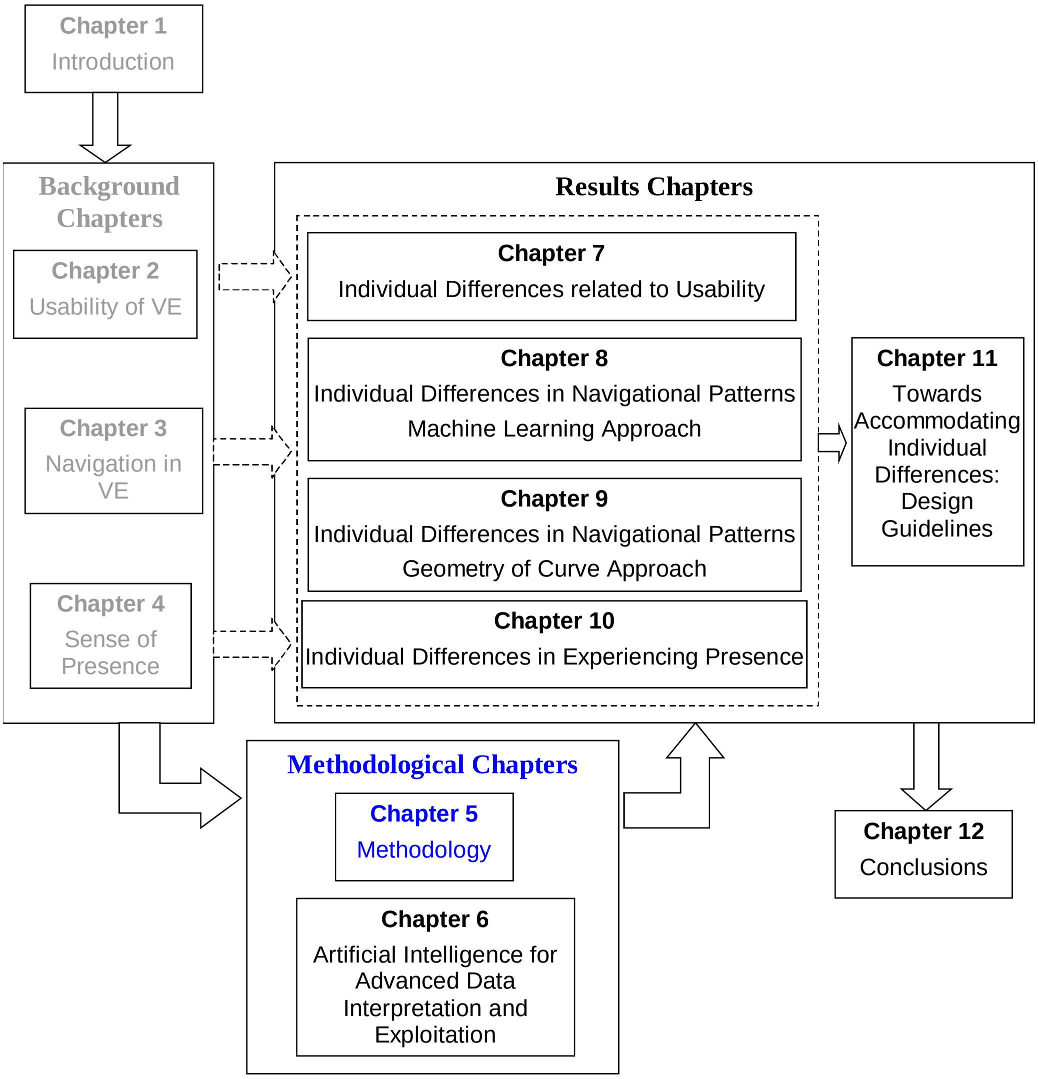

Figure 5.1: Road Map

5.1 Introduction

Scientific research methodology is a general approach to studying a research topic and logically developing an understanding of it. Its basic steps are (Heiman, 2001):

- identifying a research topic and reviewing the work which has been carried out in that area;
- developing hypotheses;
- collecting data;
- analysing data and interpreting results in the light of the previously reviewed theories and established hypotheses;
- communicating the study findings.

The *research topic* of this thesis, as outlined in Chapter 1 consists of the study of individual differences in experiencing presence and in spatial behaviours in desktop Virtual Environments (VEs). Understanding the impact of such differences on the system usability provides a basis for designing adaptive VEs which are able to accommodate these individual differences. A *literature review* has been carried out in the background Chapters 2, 3 and 4. Almost every study objective described in Chapter 1 is accomplished by formulating and testing a set of hypotheses. Study general *hypotheses* are:

1. Different spatial behaviours reflected in movement patterns are related to different navigational rules and strategies,
2. Users experience presence differently on the basis of a particular configuration of cognitive and personality factors, and
3. Accommodating such individual differences in experiencing presence and performing navigation improves the design of VE through increasing its adaptivity.

These general hypotheses will be further detailed through working hypotheses within the result Chapters 7, 8, 9, 10, and 11 which describe in detail the *data analysis* and *interpretation of findings.* With respect to *communicating the thesis findings*, the most significant results have been published in Journals and Conference Proceedings, as outlined in the list of publications.

This chapter focuses on *data collection.* It introduces the ECHOES virtual reality system, together with a detailed description of its relevant features. Those aspects, which transform ECHOES into an adequate experimental testbed for addressing study objectives are particularly discussed. Next, the study procedure depicts the tasks to be performed within the VE and offers a motivation for their selection. The variety of methods employed for gathering the data requires a brief introduction of the concept of triangulation. The measuring instruments, consisting of questionnaires developed as a result of the work carried out within this thesis, and of scales previously developed in the field, are thoroughly depicted.

5.2 Apparatus

The VR system provided by the ECHOES[1] system (O'Hare et al., 2000b) is a non-immersive training environment, which addresses the maintenance of complex industrial artefacts. Adopting a physical world metaphor, the ECHOES environment comprises a virtual multi-storey building (Figure 5.2), each one of the levels containing three rooms. ECHOES is a virtual reality system which offers a dense world, with a consistent structure. Its projection has a rectangular shape of 16×27 virtual metres. ECHOES is a large space, where in order to acquire a complete view, the user has to move and rotate. However, once the user is in a particular room, it usually requires less effort to explore it fully. Figures 5.3 and 5.4 present bird's eye views of the ground floor and first floor respectively.

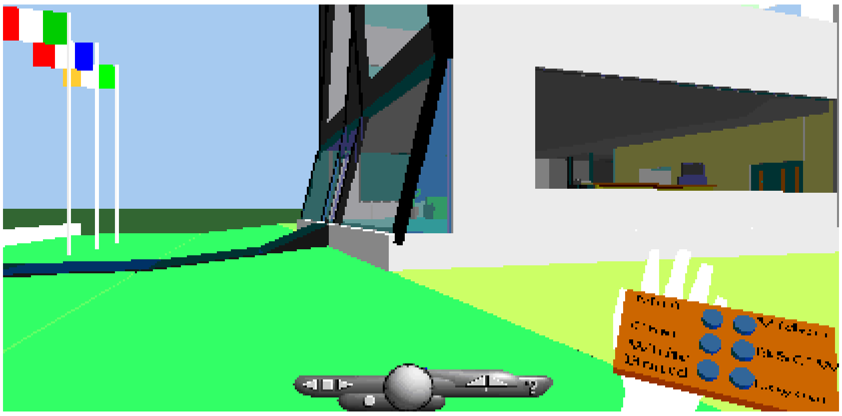

Figure 5.2: Virtual Building

Figure 5.3: Bird's Eye View of Ground Floor

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[1] ECHOES (European Project Number MM1006) was partially founded by the Information Technologies, Telematics Application and Leonardo da Vinci programmes in the framework of Educational Multimedia Task Force.

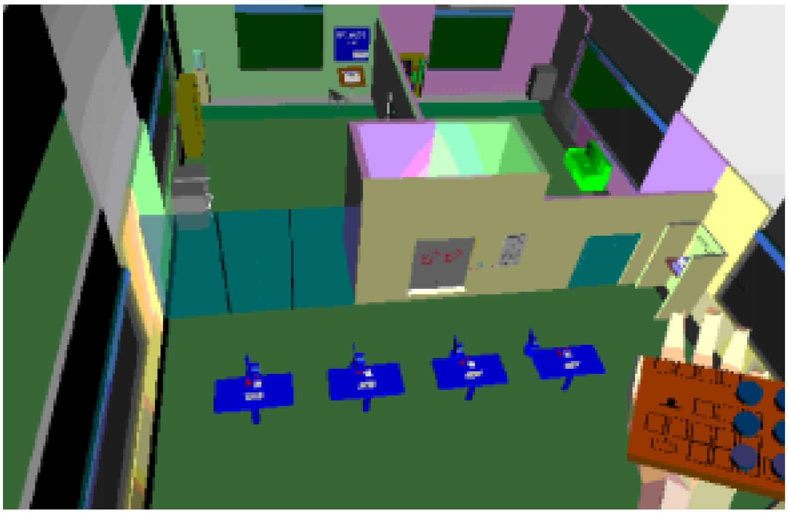

Figure 5.4: Bird's Eye View of First Floor

Snapshots for some of the rooms are presented in the following figures: lobby (Figure 5.5), library (Figure 5.6), conference room (Figure 5.7), training room (Figure 5.8), office room (Figure 5.9) etc. The rooms have adjacent walls and are connected through doors. They are furnished and associated with each room there is a cohesive set of functions provided for the user. These features enable ECHOES to offer an intuitive navigational model.

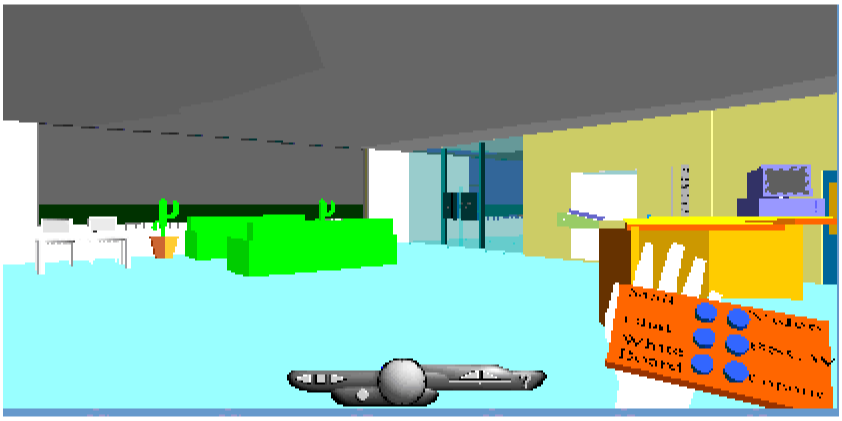

Figure 5.5: Virtual Lobby

Users can navigate in terms of moving forwards, backwards or rotating, through the use of directional keys. Every time the user presses the up-arrow or down-arrow keys, he/she performs a forward or backward translation. The longer the keys are pressed, the longer the distance covered within the VEs. Thus, the user moves in a discrete mode, at a constant speed. The height of the view point is the standard height of the avatar, (e.g. 1.70 virtual metre), while the viewing angle through which the user was enabled to perceive the virtual world was 70deg (Figure 5.10).

Collision detection was implemented using an aura paradigm. These auras surround

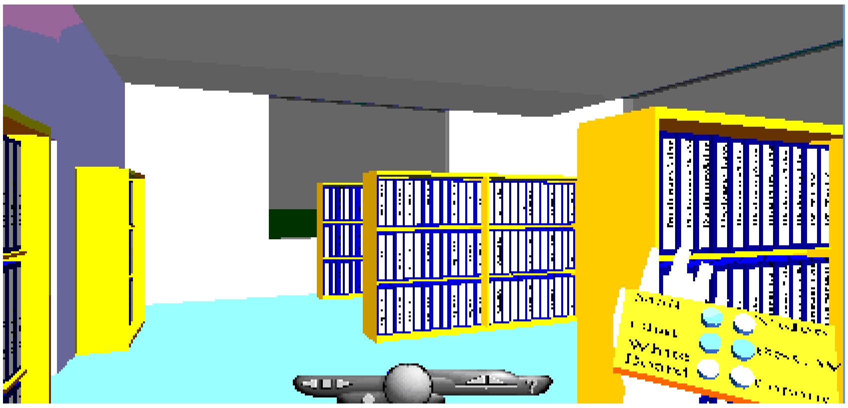

Figure 5.6: Virtual Library

Figure 5.7: Virtual Conference Room

Figure 5.8: Virtual Training Room

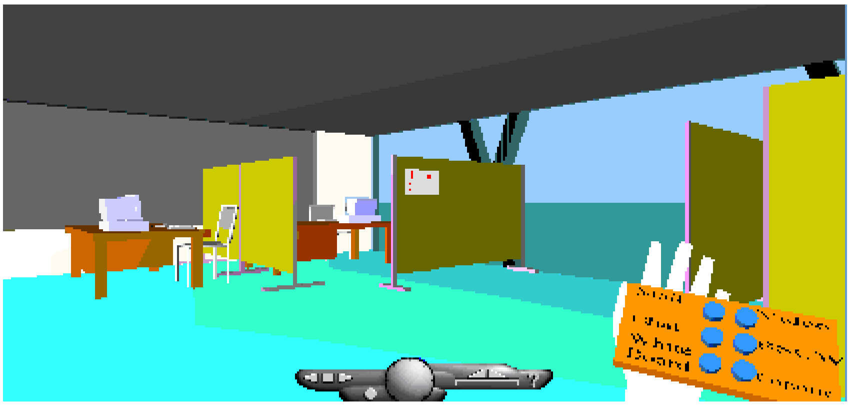

Figure 5.9: Virtual Office Room

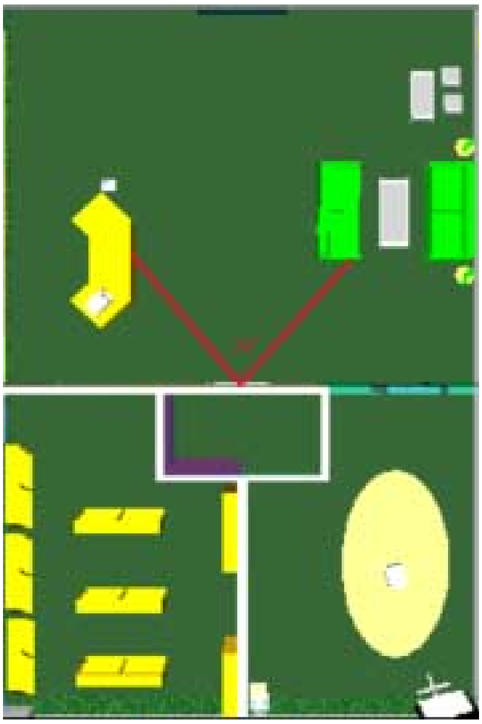

Figure 5.10: The Viewing Angle Through Which the User Perceives the Virtual World Provided by ECHOES

the objects and are proportional with objects' volume. Every time when the avatar's aura intersects an object's aura, a collision is detected.

Users merely use the mouse for selecting a new floor on the panel located in the virtual lift (Figures 5.11, and 5.12). The starting point, where the users were automatically placed at the beginning of their visit, is marked with a red arrow in the Figure 5.13. Since this point is located in front of the elevator, it represents also a starting point from exploring each level, after the user has used the virtual lift.

The ECHOES system does not provide a predefined set of paths, such as halls or corridors which would limit the user's choice of movements. Therefore, the user can move freely, being restrained only by the walls and objects located on the spatial layout.

Figure 5.11: Virtual Lift Closed

Figure 5.12: Virtual Lift Open

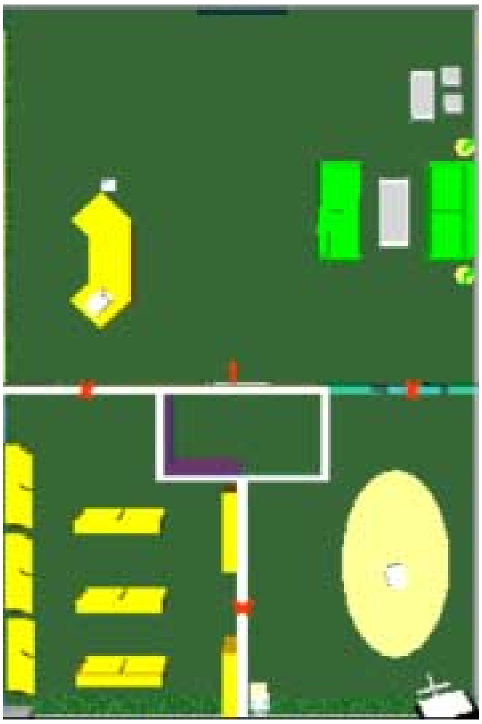

Figure 5.13: Starting Point Where User is Initially Positioned

Since the purpose was to investigate how people explore, search, and acquire spatial information about an indoor environment, this feature of the ECHOES system has been particularly exploited. The importance of unrestricting movements for investigating spatial behaviour has been previously emphasised by Darken and Banker (1998) "it is relatively free movement environment that tests navigation ability in even experienced orienteers".

Four main points can be identified in the spatial layout: the starting point in front of the virtual lift, which is also a decision point since the user is approaching it while he/she decides whether the exploration of the current level should end, and therefore another level can be chosen to be explored. The other three main points (marked with a red cross in the Figure 5.13) are the gates or doors, separating each pair of rooms. The doors are slid open when the user is in a distance range, around 2–3 virtual metres. However, the user might not be able to pass through the door if the approach angle is too sharp or too obtuse.

The ECHOES interface has been implemented using Virtual Reality Modelling Language (VRML) (Delahunty, 2001). This choice has been supported by the fact that at the time of implementation, VRML was the cutting-edge technology specialised for implementing 3D worlds over the internet. A VRML world can be viewed with any standard web browser, provided that it has an appropriate plugin. There are several such plugins, some of them being available free of charge, such as CosmoPlayer or Blaxxun Contact. The latter one was used in implementing ECHOES system (Delahunty, 2001).

5.3 Participants

The sample consisted of 32 undergraduate and graduate students from the Department of Computer Science in University College Dublin, 19 males and 13 females, within the age range 20–38. Volunteers were paid for their participation.

5.4 Procedure

The study involved three phases: familiarisation, exploration and testing or performance measurement. Initially, users were allowed to become accustomed with the VE and to learn movement control. After this, they were asked to perform an exploration task, which lasted for approximately 25 minutes.

In order to induce motivation for an active exploration, and moreover to increase the likelihood of experiencing presence, a sense of drama was induced as suggested by Laurel (1993). The instruction for the participants in the study undertaken for the purpose of this thesis was as such: "Imagine that you are following a thief who managed to steal a very valuable painting. He is now hiding inside a multi-storey building, where people are not working yet. Your task is to find the painting and catch the thief. You have only 20 minutes for this action". A colour reproduction of the painting accompanied this instruction, together with the following text: "This is the last image of the painting on the museum wall". The instructions received by participants are presented in Appendix A. This scenario involved user's direct participation, and a few of the basic components of Laurel's model: dramatic storytelling, enactment and limited duration of the action (Laurel, 1993).

This particular exploratory task was preferred to that of free wandering through the virtual building, grounded on the assumption that it could lead to an increased level of motivation and activation of cognitive resources.

Upon the completion of this task, during which participants (implicitly) acquired spatial knowledge related to VE, this knowledge was tested. Given the findings provided by studies concerned primarily with human spatial cognition, the strength of the relationship between spatial abilities measured by psychometric tests and spatial knowledge acquisition from VE is arguable (Waller, 2000). For instance, the Guilford Zimmerman (Guilford and Zimmerman, 1948) test of spatial orientation was not predictive of the survey knowledge score, nor was it predictive of any of the behavioural measures of spatial knowledge (Waller and Miller, 1998) (see Section 3.3.2). Therefore, in order to assess the level of spatial knowledge acquisition, a search task has been considered. Users were placed on the third level and asked to find a particular room located on the ground floor of the virtual building (i.e. the library). The time needed to accomplish this task acted as an indicator of the level of spatial knowledge acquired within the VE: the shorter the search time, the better the spatial knowledge (Sas and O'Hare, 2002). According to the time required for the search task, users have been identified as *low spatial users*, when they needed significantly longer time to find the library (Mean = 49 seconds), or *high spatial users* who found the library straight away (Mean = 7 seconds). Within this thesis, the terms of low versus high spatial users are related to this particular outcome and they also capture the dichotomy between poor versus good or inefficient versus efficient navigators.

Following Darkens (1996b) approach to the study of classifying wayfinding tasks, the two last phases of the experiment consist of a naive search, and a primed search (Section 2.3.2). To conclude, the primed search task offered a basis for assessing the quality of exploration and the efficiency of the exploratory strategy employed during the naive search.

5.5 Methods

5.5.1 Triangulation

The richness and complexity of human behaviour requires an investigation approach involving more than just one standpoint (Cohen and Manion, 1986). The term *triangulation* in social science was coined by Webb et al. (1966) and refers to employment of multiple methods to measure a single construct (Campbell and Fiske, 1959; Massey, 1999).

The triangulation concept, originally related to surveying, navigation and military techniques (Massey, 1999), refers to establishing the position of a point in respect to two other points or by observing it from three known positions which form three triangles whose angles are known (1991). Seen as a "sociological *navigation* techniques", triangulation can appear as (Massey, 1999):

- data triangulation, which involves data collection in a variety of settings, such as time, space, and persons;
- investigator triangulation, which consist of the use of multiple investigators, rather than one;
- theory triangulation, which consists of using more than one theoretical scheme in data interpretation;
- methodological triangulation, which involves using more than one method of collecting data.

The study carried out for the purpose of this thesis involved methodological and theoretical triangulation. Data regarding spatial behaviour has been gathered by recording the motion trajectories performed within the VE (see Section 5.8), by observing user behaviour during the tasks completion, and by video-taping these behaviours. The video recordings were used for disambiguating different aspects of data. In addition, information about how users experienced their interaction with the system, was obtained through the use of questionnaires.

Theoretical triangulation refers to the usage of different theories for data interpretation. Within this thesis, two approaches of data analysis and interpretation have been employed. Both have been focused on the analysis of the spatial behaviours performed within the VE, and both have striven to capture rules and strategies underlying such behaviours (see Section 5.9).

5.6 Measurement Instruments

Before introducing the measurement instruments, a distinction should be made between Independent Variables (IVs) and Dependent Variables (DVs). The IV is the variable directly manipulated by the experimenter, because of the assumption that it is the one that causes a change on the DV. In this study, two sets of variables (each containing both IVs and DVs) have been identified. One set reflects the impact on system usability of a set of individual differences, such as gender and prior computer games experience, while the other set reflects the impact on presence of several personality factors. In the first case, the DVs are task performance and user satisfaction, and the impact of gender, and prior computer games experience on these DVs is investigated. In the second case, the DV is sense of presence experienced by the users. Since most of the IVs that impact on presence (Absorption, Creative Imagination, Empathy) are personality traits, which cannot be manipulated, participants are assigned to a particular condition because they already qualify for that condition, e.g. more absorbed or more imaginative. Because there is no true manipulation of the IVs (except a statistical one), they are actually quasi-independent variables. The same observation applies to the predictors on system usability, such as gender and prior computer games experience.

The description of the measurement instruments is presented with respect to the study objectives described in Chapter 1. Therefore, this section is organised with respect to the instruments developed for measuring user satisfaction, for measuring presence and for measuring the cognitive factors impacting on presence. Since the first two questionnaires have been developed explicitly for the purpose of this thesis, their design will be thoroughly described.

The participants filled in all the questionnaires after the task completion, thus limiting the threat of *hypothesis guessing* to the sense of presence and user satisfaction construct validity (Trochim, 2000). Accordingly, this helped reduce the risk of contaminating the users' experience within the virtual world, by not allowing them to guess the study hypotheses. Furthermore, each of previously mentioned tools will be considered.

5.6.1 Measuring User Satisfaction

User satisfaction consists of user's attitude regarding his/her interaction with the system. User satisfaction is usually measured through self-rating questionnaires. Given the increased significance of usability-related aspects (see Chapter 2), designing proper tools for assessing user satisfaction of interaction with any type of system has become an important topic. There are several questionnaires already developed for assessing user satisfaction (Chin et al., 1988; Kirakowski and Corbett, 1990; Dumas, 1998; Lin et al., 1997). Developed with the purpose of measuring a more general construct, such as software usability, these questionnaires would not capture the fine aspects of user satisfaction when interacting with a virtual reality system. In addition, such reliable and valid instruments have been commercially developed, an aspect which imposes serious restrictions on their use, given the limited resources for carrying out this study. Therefore, for the purpose of this thesis a user satisfaction questionnaire was designed.

User Satisfaction Operationalisation

To measure any construct one should establish a connection between it and the physical reality. Translating a construct into its manifestation is the process of operationalisation (Trochim, 2000). It consists of identifying the conceptual dimensions, finding within each dimension the associated measurable variables, and choosing for each variable its actual measures in terms of indicators.

Focusing on the main aspects which might impact on user satisfaction, a set of dimensions and variables has been identified. Table 5.1 presents a description of such dimensions and variables involved by the concept of user satisfaction regarding navigational tasks.

Table 5.1: User Satisfaction Operationalisation

Dimensions	Variables
User subjective satisfaction with the system as whole	User satisfaction System requirements System features
User subjective satisfaction with different parts of system	Interface Avatar Cursor
Space configuration	Rooms Objects Depth Orientation
Locomotion	Along X axis Along Y axis Rotating Speed Bird's eye view Motion sickness
Interaction facilities	Cancel Undo Zoom Help

User Satisfaction Questionnaire

The operationalisation of user satisfaction concept served as a basis for developing a questionnaire for assessing the satisfaction with the VEs, and in particular satisfaction with the system potential for supporting spatial tasks. The user satisfaction questionnaire contained initially 20 questions with answers scored on a 7-point Likert scale, ranging from 1 (not at all) to 7 (completely). Some of these items are typical of those used for measuring user satisfaction with system interfaces (Chin et al., 1988; Lin et al., 1997). The satisfaction score was computed as the averaged of items composing the questionnaire, with mean value 4.02, median value 4, minimum value 2.64, and maximum value 5.64. Standard deviation was 0.77.

Item Analysis

Item total-correlation analysis allowed the identification of the variables that are not internally consistent with the questionnaire. Using the criterion of 0.33 as a cut-off point for retaining variables (Child, 1970; Garson, 2002), 9 items were deleted, the final questionnaire containing 11 items (see Appendix B). The results structured according to the dimensions and variables developed for questionnaire construction are presented in Table 5.2.

Users' overall satisfaction with the system is above average (score 4 on Likert scale),

Table 5.2: Mean, Median and Std. Dev. for Each User Satisfaction Variable

Dimensions	Variables	Mean	Med.(SD)
Overall Satisfaction	Frustration	2.0	2.0 (1.2)
Satisfaction regarding space configuration	Rooms	3.3	3.0 (1.2)
	Objects	3.2	3.0 (1.4)
	Depth	3.6	4.0 (1.5)
Satisfaction regarding movement	Along X axis	2.8	3.0 (1.7)
	Along Y axis	3.3	3.0 (1.2)
	Rotating	2.6	3.0 (1.3)

since the level of frustration induced by the interaction proved to be very small. Satisfaction regarding space configuration and movement is average, with a peak on depth perception.

Reliability

The questionnaire reliability has been measured with Cronbach's alpha coefficient, which is a function of the number of test items and the average inter-correlation among the items. Its values range between 0 and 1, and generally, a value of 0.70 or higher is considered acceptable in most applications (Nunnally and Bernstein, 1994). The Cronbach's alpha coefficient, $\alpha = 0.74$ indicates that the questionnaire provides reliable measurements.

The questionnaire for evaluating user satisfaction in interacting with a virtual reality system was devised in order to address the current lack of tools developed for this kind of interface and their associated range of user tasks. The findings indicate that the questionnaire provides reliable measurements, while further work should be done to validate it.

5.6.2 Measuring Sense of Presence

For measuring sense of presence, I developed a questionnaire based on the operationalisation described in the following section. Within the same research theme (i.e. presence), I also employed a battery of psychological tests aimed to assess user's empathy, absorption, and creative imagination. For a description of these constructs see Section 4.3.2.

Presence Operationalisation

According to Revonsuo (1995) immersion and sense of presence are fundamental aspects of the high level structure of the consciousness experience. Farthing (1992, p. 6) considered consciousness as “a subjective state of being currently aware of something, either within oneself or outside of oneself”. According to him, *primary consciousness* consists of direct experience and spontaneous response to it, while *reflective consciousness* focuses on conscious experience per se, which becomes the object of one's thoughts.

Kim and Biocca's (1997) findings suggested presence as a two-dimensional construct consisting of *being there* and *not being here*. Drawing a parallel with Gerrig's (1993) work in understanding the meaning of being transported by a narrative, Kim and Biocca (1997) associated these two dimensions with *the arrival in the VE* and *the departure from the physical environment*, respectively. Both these dimensions facilitate access to the content of primary consciousness. In order to also address the content of *reflective consciousness*, I consider it as an additional dimension (e.g., awareness of being there).

The variables related to the content of primary consciousness should cover the main psychological processes involved in acquiring experience, such as perception, memory, imagination, cognition, attention, emotion and action. Based on these observations, the presence variables associated with each dimension have been identified, as summarised in Table 5.3.

Table 5.3: Presence Operationalisation

Dimensions	Variables
Primary consciousness Being there (within VE)	Perceiving there Self-perception Recalling from there Imagining there Thinking there Feeling there Acting there Attentional resources
Primary consciousness Not being here (within physical world)	Not perceiving here Self-perception Not recalling from here Returning from there Not feeling here Not acting here Attentional resources
Reflective consciousness	Awareness of oneself Awareness of outside

Presence Questionnaire

In order to measure sense of presence, a presence questionnaire has been devised by the author of this thesis. It is grounded on the presence operationalisation previously described, and comprises items typical for measuring presence (Lombard, 2002).

Item Analysis

The presence questionnaire contained 34 items measured on a 7-point Likert scale, ranging from 1 (not at all) to 7 (completely). The presence score was computed as the averaged score of items composing the questionnaire, with the minimum value of 1.74, the maximum value of 5.17 and the mean of 3.38. Item total-correlation analysis allowed the identification of the variables that are not internally consistent with the questionnaire. Using the criterion of 0.33 for the loading factor as a reasonable cut-off point (Child, 1970), 12 items were deleted. The final questionnaire contains 22 items (see Appendix C). Table 5.4 presents the mean, median and standard deviation of scores along presence dimensions and variables together with the actual items. Where more items tapped the same variable, their scores were averaged. The reversed items have been marked with (R).

Table 5.4: Mean, Median and Std. Dev. for Each Presence Variable

Being there		Mean	Med.(SD)
Perceiving	To what extent did you perceive the stimuli from the remote environment as if they were real? To what extent did you perceive the desktop as a window into the virtual world? To what extent did you perceive the virtual world as images just in front of you? (R)	3.42	3.50(1.19)
Self-perception	To what extent did you perceive yourself as being engulfed in the virtual world? To what extent did you feel as if you were there?	3.43	3.33(1.29)
Imagination	To what extent were you able to imagine that world as if it were real?	3.87	4.00(1.58)
Acting there	To what extent did you act within the virtual world as if you would within the real one? To what extent did you really feel yourself navigating within another world? To what extent did you feel that the results of your interactions with the remote environment can "touch" you? To what extent did you feel as if	4.07	4.00(0.81)

Table 5.4: Mean, Median and Std. Dev. for Each Presence Variable

	you were entering the other world?		
Attentional resources	To what extent was your attention focused there? To what extent were your mental resources focused there?	5.26	5.00(0.90)
Not being here		Mean	Med(SD)
Not perceiving here	To what extent did you feel the real world as distant?	3.38	3.50(1.25)
Self-perception	To what extent did you feel that you were not permanently present in the real world?	2.68	2.00(1.37)
Not recalling from here	To what extent would you fail to recall things that happened in the real world during the experiment?	3.46	3.50(1.70)
Not acting here	To what extent did your real actions consist only of interactions with the remote world?	4.34	4.00(1.45)
Returning experience	When the experiment ended, to what extent did you feel as you were returning from somewhere else?	3.21	3.00(1.60)
Reflective consciousness		Mean	Med.(SD)
Awareness of oneself	To what extent were you aware of being there, inside the virtual building? To what extent were you aware of being no longer in the real world? To what extent were you aware of being just in front of a desktop and not inside the virtual world? (R)	3.33	3.37(1.05)
Awareness of outside	To what extent did you feel that another world existed there? To what extent did you feel the virtual world as surrounding you?	3.40	3.00(1.24)

Validity and Reliability

Despite their inherent limitations, subjective measures of presence appear to be both reliable and valid (Prothero et al., 1995a). Slater, Steed and Usoh (1993) devised a presence questionnaire (SUS) which requires subjects to rate their sense of *being there* in the VE, the extent to which the VE became their dominant reality and, the extent to which the VE became a place, rather than just images. This questionnaire has been tested and extended in several studies (Slater and Steed, 2000).

The positive statistically significant correlation $r(30) = .84$, $p < 0.01$ found between the presence scores, obtained through the questionnaire elaborated for the purpose of this thesis, with the presence measured by SUS, supports the convergent validity of this instrument[1]. The Cronbach's alpha coefficient, measuring the internal consistency of items comprising the presence questionnaire is $\alpha = 0.92$, suggesting its high reliability.

5.6.3 Measuring Cognitive Factors Impacting on Presence

The IVs were measured through a psychological test battery, consisting of Interpersonal Reactivity Index (IRI), Tellegen Absorption Scale (TAS) and Creative Imagination Scale (CIS)[2]. Willingness to Experience Presence (WEP) was measured through the following question, administrated after the task completion: "to what extent were you willing to be transported to the virtual world".

Interpersonal Reactivity Index

Davis (1994) devised a questionnaire measuring the extent to which an individual can understand someone else's thoughts, feelings and perspectives. Interpersonal Reactivity Index (IRI) contains four 7-item subscales, each measuring a separate facet of empathy. The items are assessed on a 5-point Likert scale, ranging from 0 (does not describe me well) to 4 (describes me well).

Fantasy Subscale (FS) measures the tendency to imaginatively transpose oneself into fictional situations. The Perspective Taking subscale (PT) measures the reported tendency to spontaneously adopt the others' psychological point of view in everyday life. Empathic Concern (EC) assesses the tendency to experience feelings of sympathy and compassion for others, while Personal Distress (PD) accesses the tendency to experience anxiety and discomfort from observing others' extreme distress.

I was particularly interested in identifying the correlation between FS and presence, since the ability to imaginatively transpose oneself into fictional situations could be a prerequisite for transposing oneself into a virtual world.

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[1] I wish to thank Dr. Mel Slater for allowing me to use the SUS questionnaire.

[2] I gratefully acknowledge Professor Auke Tellegen and Elizabeth Stomberg from University of Minnesota, for providing the Absorption Scale of Multidimensional Personality Questionnaire, Professor Mark Davis for his permission to use the Interpersonal Reactivity Index, and Allen Mayse from the American Journal of Clinical Hypnosis for providing the Creative Imagination Scale.

Findings suggested that the scale is both valid and reliable, with Cronbach's coefficients for each of the subscale ranging between 0.70 to 0.78. (Davis, 1983, 1980; Atkins and Steitz, 2002).

Tellegen Absorption Scale

The Tellegen Absorption Scale (TAS) is part of the Multidimensional Personality Questionnaire (MPQ) which comprises 11 subscales (Tellegen, 1982). Based upon Hilgard's (1979) findings, Tellegen (1982) and Tellegen and Atkinson (1974) developed the TAS in order to measure the extent to which people become involved in everyday events, or the tendency to totally immerse oneself with attentional objects. It contains 34 true/false questions, where each answer of true scores 1, while the others score 0. The overall score is the sum of the item scores, being within the range 0–34. The higher the score, the more absorbed is the individual. Previous findings indicate the validity of MPQ, while the internal consistency reliabilities (Cronbach's alpha) range from 0.76 to 0.89. (Krueger et al., 1996; Dana, 2000).

Creative Imagination Scale

Barber and Wilson (1979) devised Creative Imagination Scale (CIS) and showed its correlations with hypnotisability and other measures of imagination and creativity. Creative imagination also correlates with absorption (Crawford, 1982). The scale measures the ability to imagine suggested scenes and situations (e.g., setting of the sun, or the smell of ripe oranges).

It involves ten tests in which the subject is invited to imagine a number of things. By asking the participants to rate the similarity between imagined events and corresponding real events, the scale provides a measure of the vividness of imagination. The higher the score is, the better the creative imagery ability is. Study results suggest validity and reliability of this scale (Cronbach's coefficient = 0.83) (Barber and Wilson, 1979).

Myers-Briggs Type Indicator

Myers-Briggs Type Indicator (MBTI) (Myers and McCaulley, 1998) measures the strength of preference for the manner in which one processes information. Its development is grounded on Jung's (1971) theory of personality types (see Section 4.3.2), and the four basic dimensions of which are: Extraversion (E)–Introversion (I); Sensing (S)–Intuition (N); Thinking (T)–Feeling (F) and Judging (J)–Perceiving (P).

The (E)–(I) continuum explains the orientation of attentional focus as a source of energy. While (E) are energised by interacting with others, (I) are energised by their inner world of reflections and thoughts.

The (S)–(N) continuum suggests the manner of perceiving and acquiring information. (S) people are usually realistic, organised and well structured, relying heavily on their five senses to perceive information. Quite contrarily, (N) individuals are creative and innovative, looking at the overall picture rather than at its details and acting on their hunches.

The (T)–(F) continuum characterises to how one filters and organises information in order to elaborate decisions. While analysis and logics are fundamentals for (T) people, leading them to make decisions, which are strongly coherent with their principles, (F) individuals value more feelings, kindness and harmony, which drive them to decide.

The (J)–(P) continuum describes the preferred life-style and work habits. (J) individuals are those which try to order and control their world, well-organised, good planners and potentially not very open-minded. On the other hand (P) people are spontaneous, flexible, multiplex, but with a risk of not accomplishing the multiple approached tasks.

5.7 Measuring User Performance

Efficiency and effectiveness are the main aspects to be considered in relation to task performance, while together with user satisfaction they delineate the concept of usability (ISO, 1997) (see Section 2.2.1). Efficiency is considered in terms of resources required to perform the task, while effectiveness is related to the accuracy and completeness of performing the task. Both of these dimensions of task performance are measurable aspects and both have been taken into consideration in this study. The participants were asked to complete the search task not only quickly but also accurately. Therefore, I considered task performance expressed in terms of the time needed to complete the search task, which encodes efficiency, and the number of collisions encountered during navigation, which encodes effectiveness in performing the task.

5.8 Recording Spatial Behaviour Data

A comprehensive set of data was recorded throughout the experiment, by a rich set of virtual sensors. This was complemented by an odometer and a rotational event listener designed as agent-based (O'Hare et al., 2000a; O'Hare and Abbas, 1995; Delahunty, 2001; Duffy et al., 2003). The data captured when the user interacts with the ECHOES VE contains details of navigation paths along the temporal dimension and about the rotational behaviour performed by the users. Each movement greater than half a virtual metre, and each turn greater than 30 deg, were recorded. Despite the relative limited sample size (N = 32 users), a large set of data was available after the experiment. Thus, more than 200 trajectories were recorded, with an average of 160 events per trajectory (rotations and translations).

5.9 Analysing Spatial Behaviour

A main objective of this work aims to improve the understanding of how people explore the space or perform a naive search within indoor VEs. Given the significance of this issue, the analysis of user spatial behaviour, as reflected in the movement paths received considerable attention.

This analysis had a twofold purpose. Firstly, it seeks to extract navigational patterns in terms of rules or strategies underpinning the trajectory paths. As highlighted in Section 3.2.4, addressing such implicit knowledge challenges the traditional techniques of knowledge elicitation. Because of their sensitivity to learning temporal sequences — navigation is after all a spatio-temporal process — recurrent neural networks are particularly suitable for implicitly capturing such rules (Elman, 1990; Ellis and Humphreys, 1999; Ghiselli-Crippa, 2000). The richness and accuracy of the quantitative data recording users' spatial behaviours support this novel methodological approach.

Secondly, designing an adaptive VE for supporting navigation implies ensuring its sensitivity to different types of users. Such adaptive VEs should have the ability to discriminate between different groups of users, groups which should differ not only in their performance on spatial tasks, for which navigation support is primarily provided, but also in their spatial behaviour. The latter aspect, a reflection of different spatial search styles, strategies and rules, represents a basis for identifying these groups. As presented in Section 8.2, Self-Organising Maps (SOM) have been successfully employed for trajectory classification in the area of visual surveillance (Grimson et al., 1998; Owens and Hunter, 2000). The analysis of spatial behaviour which has been proposed within this thesis offers two major benefits:

- Despite the increasing usage of machine learning techniques in the area of user modelling (Kobsa, 1994), to the best of my knowledge, the potential of Artificial Neural Networks (ANNs) for analysing user spatial behaviour in VEs has never been harnessed. Thus, this research advocates for the adoption of ANN techniques for spatial behaviour analysis, aspect which constitutes a significant methodological contribution of this thesis. A detailed description of the machine learning techniques which have been employed for the work carried out within this thesis is offered in Chapter 6.
- In the attempt to increase the validity of study findings, a second approach in analysing user spatial behaviour has been employed. Apart from reinforcing some previous findings, such an additional approach would highlight new aspects, which were not captured by the initial, machine learning approach. Searching for alternative ways to analyse trajectory paths, my attention was captured by their geometric features. Comparing movement paths with some prototypical curves, would offer a considerable advantage. The equation of such curves could be used to predict motion trajectory, and therefore it could offer a valuable support for navigation assistance.

Thus, the analysis of spatial behaviour has been also performed by an approach inspired by the geometry of curve. As described in Chapter 9, Bézier curves have been successfully applied to robot navigation (Arakawa et al., 1995; Khatib et al., 1997), or avatar navigation in VEs (Chung and Hahn, 1999; Pettre et al., 2002; Boulic et al., 1994). Applying these curves for modelling trajectories followed by users, while they navigate within a VE, is another methodological contribution of this thesis.

The use of Bézier curves represents a complementary approach to the machine learning approach. It provides a basis for the diagnosis of navigational patterns and for discriminating different groups of users.

5.10 Summary

This research constitutes a case study for which the results are merely preliminary. Study limitations consist of the non-random sampling procedure for selecting participants and of relatively small sample size. These are primarily due to the limited resources of this study. The large distribution of study participants along the different dimensions of the investigated variables (e.g., personality cognitive style) is partly explained by these limitations. This probably accounts for the lack of statistical significance for some of study results. Despite the relatively small number of participants in the study, the amount of data recorded during their interaction with the VE is impressive.

Nevertheless, the above limitations reduce the generality of the obtained findings. However, the strength of study outcomes does not reside in their generalisation power but rather in their exploratory potential of identifying questions, selecting measurement constructs, developing measures and methodologies (Lynn, 1991). Further studies should be carried out in order to replicate these findings.

This chapter presented a thorough description of study methodology. It connects the theoretical chapters which have been previously described (Chapters 2, 3 and 4), with the results chapters which will follow (Chapters 7, 8, 9 and 10). The study apparatus, procedure, methods, and instruments were presented in detail. Given the significance of analysing spatial behaviour, two complementary approaches have been proposed. One involves the use of various machine learning techniques (Chapter 8), while the other one attempts to model trajectory with Bézier curves (Chapter 9). The following methodological chapter offers a review of the machine learning techniques used within this thesis.

Chapter 6

Artificial Intelligence for Advanced Data Interpretation and Exploitation

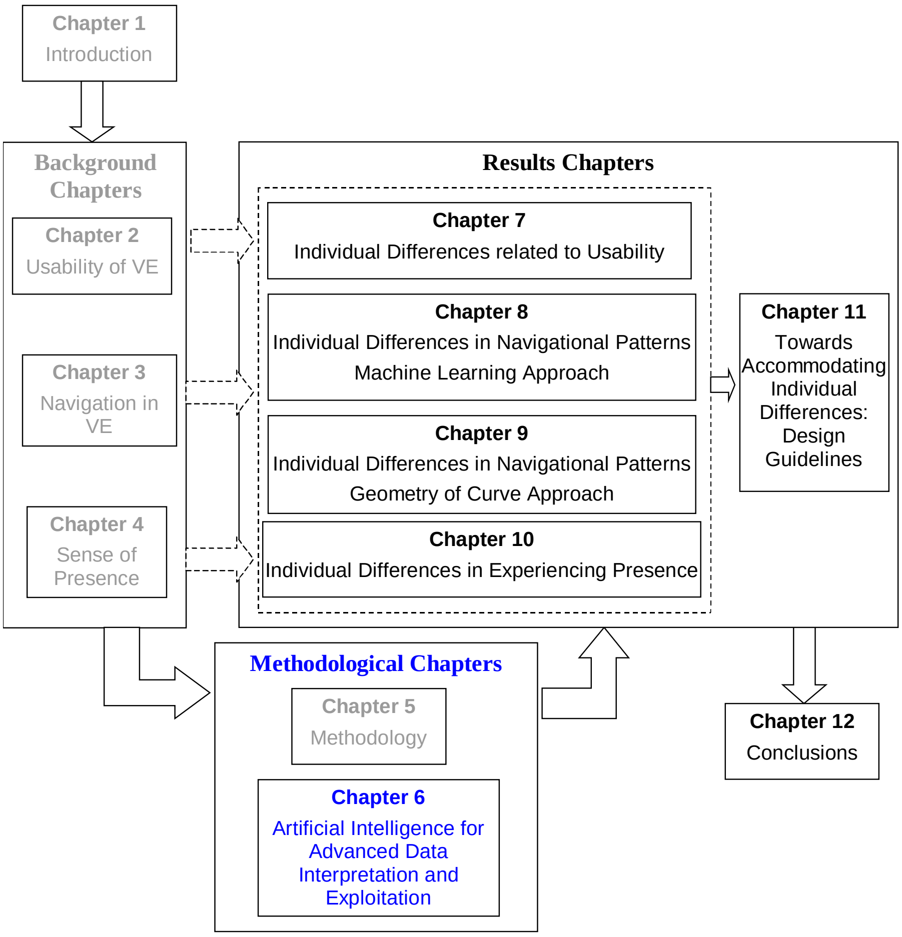


Figure 6.1: Road Map

6.1 Introduction

There are two important objectives of this thesis (see Section 5.9), supported by different machine learning techniques and intelligent agents introduced in this chapter:

- Understanding how people explore an indoor unfamiliar VE (see Chapter 1). Thus, the analysis of user spatial behaviour received considerable attention. Such an analysis aims to identify the navigational patterns which appear in users' trajectories, and to capture strategies and rules hidden in such patterns. Traditional techniques for knowledge elicitation present a series of limitations, particularly when it comes to extract implicit knowledge, inherently associated with navigational rules or strategies (see Section 3.2.4). The potential of connectionism models, and in particular of Recurrent Neural Networks (RNNs) offers an alternative approach for extracting navigational rules (see Section 3.2.4). Clustering RNN best predictions has been performed by Self-Organising Maps (SOM). In order to enable symbolic rule induction, this machine learning technique has been employed together with rule induction algorithm, (i.e. C5.0), based on the ID3 algorithm.
- Designing an adaptive VE for supporting navigation of low spatial users (see Chapter 1). The requirements of an adaptive system to accommodate users' needs (see Section 2.6.1) imply that it is capable of tailoring itself in accord to these needs. Such adaptivity is not global, and its greatest potential resides rather in system's capacity to address specifically the different needs of *different groups* of users. Therefore, an important characteristic of an adaptive system would be the capacity to identify the groups of users which require different adaptations. Such groups should differ both in their performance, reason to provide navigation support, but also in their navigational behaviour (see Section 5.9). The navigation behaviour, an expression of different spatial strategies and rules allows an online and unobtrusive identification of these user groups. Trajectory classification presents an appealing potential for performing such kind of identification. The use of SOM provided encouraging results for trajectory classification in the area of visual surveillance (Grimson et al., 1998; Owens and Hunter, 2000) (see Section 8.2). Within this thesis, SOM was used together with Learning Vector Quantisation (LVQ) (see Section 6.4.4).

  The adaptive version of ECHOES system is designed through the use of intelligent agents, used to implement the identified efficient navigational rules and strategies for assisting low spatial users. The choice of designing a multi-agents adaptive ECHOES VE is motivated by the agent-based architecture supporting the non-adaptive version of ECHOES VE (see Section 11.4.6).

This chapter offers a review of different Artificial Intelligence (AI) techniques for advanced data interpretation and exploitation, which have been used within this thesis. These techniques are organised in two main classes: machine learning techniques and intelligent agents. The presentation of machine learning techniques is organised according to two fundamental classes of machine learning algorithms: supervised and unsupervised learning. Intelligent agents are introduced in the context of the Agent Factory, an agent developing environment. The benefit of these techniques for designing adaptive VEs is further discussed.

6.2 Machine Learning Techniques for User Adaptive Systems

Machine learning is an area of AI research concerned with computational theories of learning processes and building machines that learn from experience (Gilmore and Self, 1988). Mitchell (1997) proposed an operational definition of machine learning as the designing "computer programs that automatically improve with experience".

The main goal of machine learning algorithms is generalisation, or the ability to reach more general concepts, by searching domain specific concepts, or in other words to improve the performance based on past experience. In the context of machine learning, learning can be described as finding a hypothesis h: X → Y which maps all input states X to an output Y with high accuracy. Since only a subset of X is presented to the system during training, the learning is considered as being an inductive process (Schmid, 1998).

User Adaptive Systems have been described in Section 2.6. In short, such system learns something about each user for the purpose of adapting its behaviour to him/her. As Jameson (2003) pointed put, significant features of these systems reside in their potential for learning and making inferences about user behaviour, and in their decision making ability when it comes to adjusting system behaviour with respect to user needs or requirements. In this context, a central role is played by those techniques employed for user model acquisition and applications. These techniques, usually borrowed from the machine learning field, enable a system to learn the behavioural patterns of its end-users and to make inferences based on this knowledge. A distinct category of machine learning technique has emerged and has been successfully employed by different user adaptive systems.

> Despite their specific, these methods share the basic nature of a classification learning problem: the learning process starts with a set of training examples, each of which is characterised in terms of its features. Each training example has been classified, that is, assigned to one of a set of categories. On the basis of these examples, the procedure learns a classifier: a model that is capable of assigning a new item to one of the same set of categories (Jameson, 2003).

In addition, these techniques are able to exploit not only explicit self-reports provided by the users, but they work well with no explicit inputs, such as "naturally occurring actions", which do not require any additional user's investment (Jameson, 2003).

6.2.1 Machine Learning for Studying Cognitive Models

The classical methods for studying cognitive models (see Chapter 3) such as interviews, protocol analysis or map drawing present limitations related primarily to the implicit content of the information which researchers try to elicit. Since this would require a high level of introspection, usually users face difficulties in externalising or bringing into the consciousness these models, of which they are not aware. If the information is elicited during the task completion, the risk of interference with the task or the risk of cognitive overload arises. In both of these cases task performance is contaminated and no longer valid. If the attempt of accessing the mental models is done after the task has been completed, the risk of post rationalisation arises (the user tries to explain, interpret or make sense of his behaviour, which is not what a mental model analysis strives to achieve). In addition, the manner in which the model is externalised (i.e. verbally or drawing), implicitly assumes a particular set of skills, whose absence impedes the externalisation of the mental model.

In the attempt to overcome these limits, I searched for alternative methods, inspired by the tools and techniques developed in the area of machine learning. This work proposes a hybrid connectionist-symbolic model for investigating and extracting rules governing human spatial behaviour.

6.2.2 Machine Learning Algorithms

Langley (1997) defined a machine learning algorithm as “a software system that improves its performance in some task domain based on partial experience with that domain”. The machine learning algorithms, which are discussed within this chapter and used in the thesis, are divided into two categories. Those which can be classified as unsupervised learning algorithms and those which are supervised. Algorithms that require a set of pre-classified examples are referred to as supervised learning algorithms as opposed to unsupervised when this is not a requirement. Furthermore, each of them will be considered in turn.

6.3 Unsupervised Learning

Machine learning algorithms which do not require a class, associated with each example within the training set are called unsupervised. In other words, the unsupervised learning algorithms fit a model to a set of training data which does not have any a priori outputs.

Numerous unsupervised algorithms have been developed in the last forty years, such as K-means clustering (MacQueen, 1967; Anderberg, 1973), hierarchical clustering (Anderberg, 1973), principal component analysis (Jolliffe, 1986; Jain et al., 1999) and so on. Beside them, new unsupervised learning algorithms such self organising networks have been developed. Self-Organising Maps (SOM) are a type of Neural Network (NN) and are the only unsupervised learning algorithm which have been used in this thesis twice: for trajectory classification (Section 8.2) and for clustering the best prediction of the Recurrent Neural Network (RNN) (Section 8.3). This algorithm will be further discussed.

6.3.1 Self-Organising Maps

A basic SOM consists of an input layer, an output map and a matrix of connections between each output unit and all the input units. The input is usually represented by a multidimensional vector with each unit coding the value from one dimension. Every node from the two-dimensional output layer is associated with a so-called reference vector (m_i), consisting of a set of weights from each input node to the specified output node. In a simplistic way, each input vector is compared with all the reference vectors and the location of the best match in some metric, usually the smallest of the Euclidean distances, is defined as the winner. Around the maximally responding unit, a topological neighbourhood is defined and the weights of all units included in this neighbourhood are adjusted, according to equation 6.1, where m_i is the weight at time $(t+1)$ and η is the learning rate.

$$m_i(t+1) \quad = \quad m_i(t) + \eta \cdot [x(t) - m_i(t)]. \tag{6.1}$$

The topological neighbourhood should be quite large at the beginning, to enable a global order of the map, while in the subsequent stages its values decreases as a function of time. Accordingly, the learning rate varies in time from an initial value close to unity, to small values over a long time interval.

Training is performed during two phases: an ordering phase during which the reference vectors of the map units are ordered (neurons in different areas of the network learn to correspond to coarse clusters in the data), and a much longer fine-tuning phase during which the reference vectors in each unit converge to their correct values (neurons adjust to reflect fine distinctions).

The learning process consists of a “winner-takes-all” strategy, where the nodes in the output map compete with each other to represent the input vectors. For this reason, the output layer is also called the competitive layer. Competitive learning is an adaptive process, through which the neurons from the output layer become slowly sensitive to the input data, learning to represent better different types of inputs.

As Kohonen (2001) pointed out, a significant property of SOM is the tendency to preserve continuity in terms of mapping similar inputs to neighbouring map locations influenced by the weight vectors trying to describe the density function of the input vectors. As a result of these antagonistic tendencies, the distribution of reference vectors is rather smooth, given the search for an optimal orientation and form to match those of the input vector density. In addition, the greater the variance between the input vector features, the better their representation on the output map. It is expected that these features correspond to the most important dimensions of the inputs.

SOM_pak

The SOM algorithm has been developed by Teuvo Kohonen and implemented by his team from Helsinki University of Technology, in the form of SOM_pak (Kohonen et al., 1996).

SOM vs. LVQ

While the SOM algorithm strives to approximate the weight vectors to the input ones, LVQ tries to lead to weights that effectively represent each class. The process of adjusting the weights, without respect to any topological neighbourhood differentiates LVQ from SOM. The performance of LVQ can be increased by initialising the codebook vectors with those values obtained by training the SOM (Kaski, 1997). Variants of SOM have been successfully applied to a large number of domains, ranging from monitoring and control of industrial tasks, to robot navigation, from data processing to machine vision, from image analysis to novelty detection (Kaski, 1997). However, their adoption within the frame of spatial cognition in VE constitutes a novel approach.

6.4 Supervised Learning

Supervised learning is a class of algorithms which create a function from training data consisting of both inputs and desired outputs. The task of supervised learning algorithms is to predict the value of this function for any valid input after having seen only a small number of training examples. This is possible only when the learner has been able to generalise from the training set to unseen inputs.

Several supervised algorithms have been developed, such as: Artificial Neural Networks (ANNs) (Haykin, 1994), decision trees (Utgoff, 1989), ID3 algorithm (Quinlan, 1993), Learning Vector Quantisation (LVQ) (Kohonen et al., 1995), instance-based learning (Aha, 1990), support vector machines (Cristianini and Shawe-Taylor, 2000), deterministic Boltzmann machines (Kappen, 1995), linear least squares (Bradtke and Barto, 1996) etc. Among these various algorithms, the following four have been be used in this thesis because of a twofold reason.

- Artificial Neural Networks
- Decision Trees
- ID3 algorithm
- Learning Vector Quantisation

These four algorithms present features which made them suitable candidates for the tasks they were required to achieve. The findings described in Chapter 8 argue for the plausibility of these algorithms in the context of this thesis. In addition, an economical reason supported the choice of these particular algorithms. Some of them are implemented in software packages which are freely available, while the licence for the other has been previously acquired by the Department of Computer Science, University College Dublin. Each of these four algorithms is further discussed.

6.4.1 Artificial Neural Network

Neural networks have proven particularly suited to finding patterns in large amounts of complicated and imprecise data, and detecting trends that are too complex to be noticed by humans (Christos, 1996). While neural networks have been fruitfully exploited by artificial intelligence researchers, their adoption within HCI is very limited. They have been primarily applied to pattern recognition (Preece et al., 1994). Finlay and Beale (1992) identified four areas of HCI which involve pattern recognition problems, such as task analysis and task evaluation, natural interaction methods such as gesture, speech, handwriting, and adaptive interfaces.

Artificial Neural Networks (ANNs) provide a very powerful toolbox for modelling complex non-linear processes in high dimensionalities (Lint et al., 2002). ANNs have many advantages over the traditional representational models, particularly distributed representations, parallel processing, robustness to noise or degradation and biological plausibility (Haykin, 1994). At least part of these strengths can be harnessed to model user's behaviour in terms of spatial knowledge acquisition.

The perceptron is the simplest form of NN used for the classification of linearly-separable patterns (Haykin, 1994). The multilayer perceptron represents a generalisation of the single layer perceptron (Figure 6.2) involving a popular supervised learning algorithm such as *error back-propagation.* The purpose of error back-propagation algorithm is to minimise the error between network output and training samples. The error back-propagation process consists of two phases (Haykin, 1994). In the *forward pass*, an activity pattern is applied and its effect is propagated through the network which

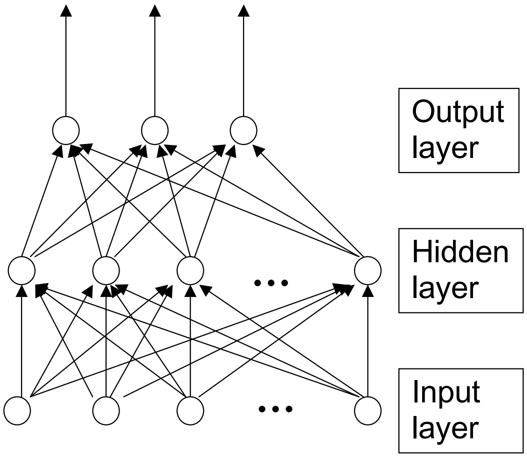


Figure 6.2: Architectural Graph of a Multilayer Perceptron with One Hidden Layer

produces a set of outputs, according to equation 6.2:

$$y_k(t) = f_n\left(\sum_{i=0}^{n-1} w_{ki}(t)\cdot x_i(t) - \phi\right), \tag{6.2}$$

where $y_k(t)$ is the output of neuron k at time t, $x_i(t)$ is input node i at time t, $w_{ki}(t)$ is the weight from input $x_i(t)$ to the output node $y_k(t)$, and ϕ is the threshold value. While within this phase the weights are fixed, during the *backward pass* they will be adjusted according to the error-correction rule (equation 6.3):

$$w_{ki}(t+1) = w_{ki}(t) + \eta[d_k(t) - y_k(t)]\cdot x_i(t), \tag{6.3}$$

where η is the *learning rate* ranging from 0.0 to 1.0 which controls the adaptation rate.

The network response is subtracted from the target response to produce an error signal, which is propagated backwards through the network. The error back-propagation algorithm is summarised in Algorithm 1.

Algorithm 1 Error Back-Propagation Algorithm

```
Require: Input values and target output values for both training and testing set
Ensure: Set of weights
initialise weights to small random values
for all inputs in training set do
    present the input and desired output
    starting from input layer and go through the network to calculate activations for all units
    calculate the error for the output units
    starting from output layer and go through the network to calculate the errors for all units
    adjust the weights according to the calculated errors
end for
calculate the global error
```

Despite its popularity, standard back-propagation presents a major limitation in terms of its ability to process only static input–output mapping (Haykin, 1994). Cognitive processes always unfold in real time (Gelder and Port, 1995). The temporal dimension is significant for learning, and in particular for all cognitive processes of higher order such as vision, speech and nevertheless navigation. Representing time within the multilayer perceptron should address the practical problems of how to provide it with memory (Elman, 1990).

The role of memory is to transform a static network into a dynamic one, whose output becomes a function of time. A basic dichotomy considers *short-term* and *long-term* memory, according to the retention time. Usually, long term retention is built into memory through supervised learning which allows the information content of the training set to be stored in the synaptic weights of the network. However, if the task has a temporal dimension, it is short-term memory which makes the network dynamic, through the use of time delays. Recurrent Neural Networks (RNNs) have been developed to address this aspect and therefore they are perfect candidates to learn sequential patterns.

Recurrent Neural Networks

A RNN is a neural network with feedback connections (Fausett, 1994). An important application of RNN is the modelling of dynamic systems involving trajectories, which are good examples of events which specifically involve temporal relationships. Typical cases are the famous non-linear and autonomous dynamic systems of the circle and the figure-eight (Unadkat et al., 1999). Training data consist of inputs and their desired successor outputs. The net can be trained to predict the next input in a sequence. If VEs are helpful to predict human behaviour, than they should hold some promise for enabling our understanding of it (Waller, 2000).

Simple Recurrent Neural Networks Elman's (1990; 1991) network is a partially recurrent neural network (see Figure 6.3). The connections are mainly feed-forward but also include a set of carefully chosen feedback or recurrent connections which provide the network with a dynamic memory and allows cues from the recent past to be remembered (Plunkett and Elman, 1997).

Architecture The architecture of Simple RNN is based on four types of neurons:

- Input neurons which receive information directly from the input patterns;
- Output neurons which provide the response learned by the network;
- Hidden neurons whose major role consists of discovering the significant features within the input patterns;
- Context neurons which store short-term memory of the network, in terms of the hidden node activation patterns from previous time step.

One observation should be made with respect to the context nodes. They provide the sequential context and their weights are processed as those for the input units. The hidden nodes activation pattern at one time step will be fed back to the hidden nodes at the next time step, along with the input pattern. The role of these context units has been described as follows:

> In the present architecture (Figure 6.3), the context units remember the previous internal state. Thus, the hidden units have the task of mapping both an external and also the previous internal state to some desired output. Thus, the internal representations that develop are sensitive to temporal context; the effect of time is implicit in these internal states (Elman, 1990, p. 6).

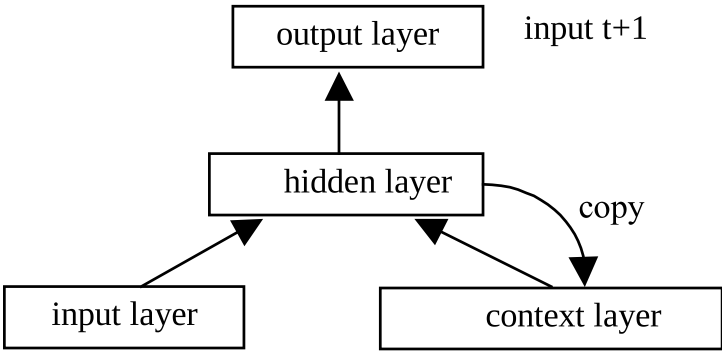


Figure 6.3: Simple Recurrent Neural Network Architecture

Evaluating Network Performance Network performance can be evaluated in several ways (Plunkett and Elman, 1997):

- Global error which reflects the discrepancy between the actual network output activation and the target activations. As learning progresses, the error decreases, ideally becoming zero. However, in the context of non-deterministic tasks, the network will still produce some error, since it learned only the correct probabilities.
- Individual pattern error could highlight patterns of interest, which have been learned very well or not at all, as opposite to the rest of them. This analysis goes beyond the global error, which average the errors for all the patterns and whereby the interesting patterns remain hidden.
- Analysing weights and internal representations. In order to understand the internal representation of patterns that the network succeeded to achieve, one could employ hierarchical clustering of hidden node activations. This approach is justified by the fact that inputs which are seen as similar by the network usually produce internal representations closer to each other.

SNNS

The RNN simulation carried out in this thesis (see Section 8.3) was performed using Stuttgart Neural Network Simulator (SNNS) (Zell et al., 1995). SNNS is a commonly used software simulator, developed at the Institute for Parallel and Distributed High Performance Systems at the University of Stuttgart. SNNS is available for Unix and Windows platforms and supports different network topologies. In addition, it is highly configurable and includes a relatively large number of learning procedures such as: backpropagation algorithms, Kohonen networks, time-delay and recurrent networks. The graphical user interface offers a 2D/3D representation of the neural networks and allows a user-friendly control of the kernel during the simulation run. The sources of C implementation are freely available and can be easily extended with user-defined libraries (Marian, 2002).

6.4.2 Decision Trees

A decision tree is a representation of a decision procedure for determining the class of an object or instance, by testing its value for certain properties (Utgoff, 1989). An attribute describes a characteristic of an instance. Given a set of instances, known as the training set, the algorithm searches through this space to create a decision tree that classifies adequately instances in the set. A decision tree consists of:

- Leaf nodes which indicate the value of the target attribute or the class label for a given instance,
- Decision nodes which represent an attribute test to be carried out on a single attribute-value.

The decision tree algorithms approach the classification problem in a divide-and-conquer manner. Thus, through a top down induction of decision trees, the classification starts from a root node and generates sub trees until leaf nodes are created. At each stage, the algorithm searches for an attribute to split on, namely the one that separate the classes best. The algorithm repeats itself recursively by processing the divisions resulted from the split. The key requirements for employing decision trees are:

- There should be a fixed collection of attributes or properties, which provide information for each object or case. These attributes should have discrete values.
- There should be a predefined set of classes. Since decision tree is a supervised learning technique, the categories or classes to which objects are to be assigned must have been previously established.
- The classes should be clearly defined, such that each case belongs to one and only one class and there must be more cases than classes.
- There should be sufficient data, in terms of hundreds or even thousands of training cases, in order to allow the identification of patterns from chance coincidence. The amount of data required depends on the number of attributes, number of classes and the complexity of the classification.

6.4.3 ID3

J. Ross Quinlan (1993) developed ID3, based on the Concept Learning System (CLS) algorithm, which has been enhanced by adding windowing and information theoretic heuristic. The central focus of the ID3 algorithm is selecting the attribute to be tested at each node in the tree. In order to decide which attribute is the best, the ID3 algorithm uses a statistical property called *information gain.* This measure assesses the ability of a given attribute to separate the instances into targeted classes. The attribute presenting highest information gain is selected.

In order to measure *information gain*, one should introduce *entropy*, defined as the impurity of an arbitrary collection of examples. Given a set S, containing only positive and negative examples of some concept with only two target classes, the entropy is:

$$Entropy(S) = -p_p \cdot \log_2 p_p - p_n \log_2 p_n, \tag{6.4}$$

where p_p is the proportion of positive cases and p_n is the proportion of negative cases at the node. If the target attribute takes on t different values, then the entropy of S relative to this t-wise classification is defined as

$$Entropy(S) = \sum_{i=1}^{t} -p_i \cdot \log_2 p_i, \tag{6.5}$$

where p_i is the proportion of S belonging to class i.

Given *entropy*, the *information gain* related to an attribute will be the expected reduction in entropy caused by partitioning the examples according to that attribute. $Gain(S, A)$ of an attribute A, relative to a collection of examples S, is:

$$Gain(S, A) \;\; = \;\; Entropy(S) - \sum_{v \in V(A)} Entropy \frac{\|S_v\|}{\|S\|} \cdot (S_v), \tag{6.6}$$

where values (A) is the set of all possible values for attribute A, and S_v is the subset of S for which attribute A has value v. The first term in the equation 6.6 is the entropy of the original collection S, while the second term is the expected value of the entropy after S is partitioned using attribute A.

The process of selecting a new attribute and partitioning the training examples is now repeated for each non-terminal descendant node, this time using only the training examples associated with that node. Attributes that have been incorporated higher in the tree are excluded, so that any given attribute can appear at most once along any path through the tree. This process continues for each new leaf node until either of two conditions is met:

- every attribute has already been included along this path through the tree, and
- the training examples associated with this leaf node have the same target attribute value, and their entropy is zero.

To summarize, the ID3 algorithm is given in Algorithm 2.

C5.0 package

Based on the algorithm ID3, Quinlan (1993) developed C4.5, and its commercial version C5.0, a package for decision tree induction and rule production. The decision tree generator takes as input a training set of case descriptions or instances described on the bases of their values for a set of attributes. It produces as output a decision tree which strives to achieve a generalised classification scheme based on the cases seen in the training set. The production rule generator constructs from the original decision tree a set of rules, expressed in the form of IF–THEN (Figure 6.4). Usually, the rules offer

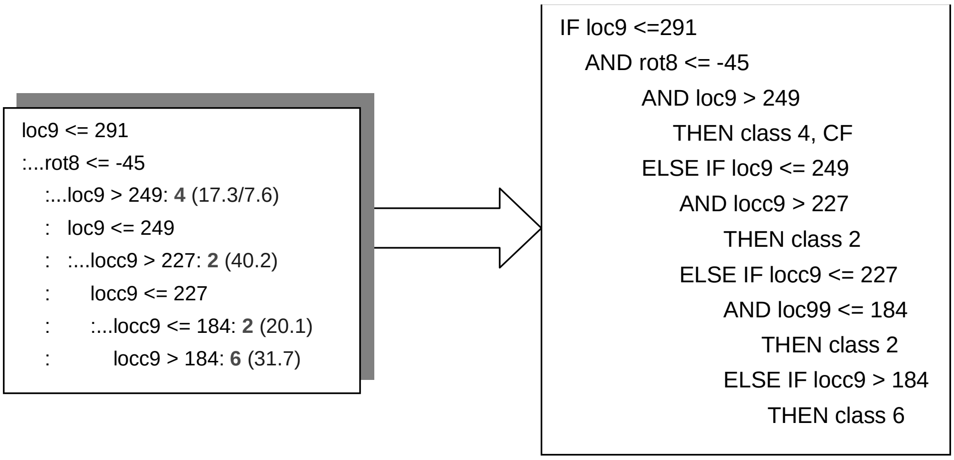
Algorithm 2 ID3

```
Require: A training set I of instances $i_k$, described along a set A of attributes $a_l$ and a set C of classes $c_m$ or target attributes.
Ensure: Decision tree
if I is empty then
    return a node with value Failure
end if
if each instance $i_k$ belongs to the same class then
    return a single leaf node with that value
end if
if A is empty then
    return a single node with the value of the most frequent class value
else
    for all attributes do
        compute entropy and information gain
    end for
end if
select the attribute $A_{lowestentropy}$ with the lowest entropy
return a tree with root node for the attribute $A_{lowestentropy}$
divide data into separate sets so that within each set, $A_{lowestentropy}$ has a constant value
return a tree with different branches for each value of the attribute $A_{lowestentropy}$
if $A_{lowestentropy} = a_t$ then
    return subtree $t$
    while there are no attributes left or all $i_k$ in the sub tree belong to the same class do
        for each subtree repeat the algorithm by computing the $A_{lowestentropy}$ do
            remove the processed attribute
        end for
    end while
end if
```

a more flexible and comprehensible representation than the decision trees. In addition, rules are more accurate when generalising to unseen cases than the original trees.

6.4.4 Learning Vector Quantisation

LVQ is a supervised learning algorithm related to SOM. LVQ consists of an input layer comprising multidimensional vectors described by their features and an output layer whose neurons correspond to the predefined classes. There is also a matrix of connections between each output unit and all the input units, consisting of weights vectors. Since each weight vector corresponds to a class, the vectors are considered as labelled. The basic idea is that input vectors belonging to the same class will cluster in data space, in a form of a normal distribution around a prototype vector. Classifying an input vector consists of computing the Euclidean distance between the considered input vector and all the weight vectors, followed by assigning it to the class associated with a weight vector for which the Euclidean distance is minimum (Kohonen et al., 1995).



```
loc9 <= 291
:...rot8 <= -45
    :...loc9 > 249: 4 (17.3/7.6)
    :   loc9 <= 249
    :   :...locc9 > 227: 2 (40.2)
    :       locc9 <= 227
    :       :...locc9 <= 184: 2 (20.1)
    :           locc9 > 184: 6 (31.7)
```

```
IF loc9 <=291
   AND rot8 <= -45
         AND loc9 > 249
             THEN class 4, CF
         ELSE IF loc9 <= 249
              AND locc9 > 227
                   THEN class 2
              ELSE IF locc9 <= 227
                   AND loc99 <= 184
                        THEN class 2
                   ELSE IF locc9 > 184
                        THEN class 6
```

Figure 6.4: Decision Tree

During training, an adaptive process occurs with respect to the closest weight vector, also called the winning neuron. When both the input vector and the weight vector belong to the same class, meaning that the input vector was correctly classified, the weight vector is modified in order to become a better approximation of the input vector. However, when the input vector is incorrectly classified, the weight vector is adjusted in a way which increases its distance of the input vector (since they belong to different classes).

LVQ_pak

The LVQ algorithm has been developed by Teuvo Kohonen and implemented by his team from Helsinki University of Technology, in the form of LVQ_pak (Kohonen et al., 1995).

After describing the relevant machine learning techniques which have been employed within this thesis, the following section introduces *intelligent agents*, as an important application area for machine learning. A presentation of their relevant features aims to provide a rationality for the use of agents in order to support the building of the adaptive VE (see Section 11.4.6).

6.5 Intelligent Agents

Intelligent agents offer a radical alternative to conventional software development approaches. While there is no generally accepted definition of *agents* in AI, many efforts have been made and different theories and architectures arisen. In a general sense, an agent is a program that can run autonomously in order to accomplish tasks without direct human supervision. For the purpose of this thesis, the following understanding of the agent, as proposed by Shoham (1993), is considered:

> ... an entity whose state is viewed as consisting of mental components such

> as beliefs, capabilities, choices and commitments. These components are defined in a precise fashion, and stand in rough correspondence to their common sense counterparts. In this view, therefore, agenthood is in the mind of programmer. What makes any hardware or software component an agent is precisely the fact that one has chosen to analyse and control it in these mental terms.

In order to exhibit an intelligent behaviour, an agent should be built to meet several criteria. Weld (1995) summarises five attributes which capture the essence of an intelligent agent:

- *Integrated*: The agent must support an understandable, consistent interface;
- *Expressive*: The agent must accept requests in different modalities;
- *Goal-oriented*: The agent must determine how and when to achieve a goal;
- *Cooperative*: The agent must collaborate with the user;
- *Customised*: The agent must adapt to different users.

To conclude, an intelligent agent must be capable of autonomous, customised, goal-oriented behaviour, thus acting as a personal assistant to the user. In this research, the goal is to create intelligent agents that perform customised, dynamic adaptation (e.g. reconfiguration of VE).

6.5.1 Agent-Based Systems

Due to their specific, machine learning techniques can be successfully employed for building agent-based systems. Such agents would be able to work in partially understood environments used by a large variety of users with a dynamically changed behaviour. These agents are also able to operate in real time, to learn from experience, and to adapt to unforeseen situations. The most important aspect, for the purpose of this thesis consists of the fact that agents are able to capture the unspecified and/or changing preferences of these users, and therefore can serve better the system functionality, for increased usability.

Agent Factory

Several platforms and development tools for agents have been developed, supporting in particular the implementation phase. Some of these platforms comply with the Foundation for Intelligent Physical Agents (FIPA) (FIPA, 2003), which is a body currently working in the area of agent standardisation. The most important of these systems are: Zeus (Nwana et al., 1998, 1999), FIPA Open Source (Poslad et al., 2000), JADE — a Java Agent Development Framework (Bellifemine et al., 1999), and LEAP — Lightweight and Extensible Agent Platform (Bergenti and Poggi, 2001).

Agent Factory (O'Hare and Abbas, 1995; O'Hare et al., 2000a; Collier et al., 2003) is an academic prototype, developed and maintained in-house at University College

Dublin. The non-adaptive version of the ECHOES system has been developed on an agent-based architecture, supported by Agent Factory. Thus, this platform has been used for designing the adaptive version of ECHOES VE (see Section 11.4.6).

Agent factory provides a cohesive framework for the development and deployment of agent-based applications. In particular, it provides extensive support for the creation of Belief Desire Intention (BDI) agents. This agent type is realised through the implementation of some mental state architecture and a corresponding agent interpreter that manipulates the mental state, allowing the agent to reason about how best to act.

The framework itself is implemented in Smalltalk-80, while a more recent version has been developed using Java. The Agent Factory runtime environment consists of:

- *Agent Virtual Machine* which contains the kernel of the Agent Factory platform including the deductive apparatus for the BDI agents;
- *Message Transport System* which manages the delivery of messages both between agents on the same platform and between agents on different platform;
- *Migration Manager* which oversees the migration of agents between different platforms;
- *White Pages Agent* which supervises the agent platform and manages the creation and deletion of agents.

BDI concepts are fundamental to Agent Factory and its agent structure reflects this, through the following components describing every agent:

- a mental state,
- commitment rules,
- actuators, and
- preceptors.

An agent's mental state contains the agent's current model of itself and its environment. This knowledge is represented as beliefs. Current beliefs refer to beliefs that are held about the current state of the environment at a single point in time, while temporal beliefs have some temporal attribute associated with them. Such beliefs are essential for representing knowledge that is of a persistent nature.

Commitment rules describe the situation under which an agent may adopt a certain commitment. A commitment in Agent Factory is some action that the agent wishes to perform. After deliberating on its belief set and reconciling them with its commitment rules, an agent will adopt a commitment, in terms of committing to carrying out some course of action.

Actuators must be explicitly programmed and their remit is to affect the required changes in the agent's environment as a result of the commitments it has adapted.

Preceptors constitute the functional units that an agent uses for building a model of its environment. These must be explicitly programmed and generate an appropriate belief set that represents a true model of the current state of the agent's environment.

6.6 Summary

This chapter provided detailed descriptions of various machine learning algorithms which are used in this thesis. Previously outlined features of these algorithms, further detailed in Chapter 8, argues for the suitability of this particular set of machine learning techniques, for addressing study objectives. The availability of the software packages supporting the implementation of these techniques constituted an additional factor which guided their choice.

Obviously, other clustering techniques (e.g. K-means clustering (MacQueen, 1967; Anderberg, 1973), hierarchical clustering (Anderberg, 1973), principal components analysis (Jolliffe, 1986; Jain et al., 1999) etc.), rule induction algorithms (McMillan et al., 1992), case-based reasoning algorithms (Riesbeck and Schank, 1989; Aamodt and Plaza, 1994), or neural networks able to deal with time series processing (e.g. recurrent SOM (Koskela et al., 1998), temporal SOM (Kangas, 1990; James and Miikkulainen, 1995) etc.) could have been considered. However, at this point, the interest was primarily to expand the currently used methodologies and tools in order to overcome their limitations, rather than proposing the best methodology. Study findings (see Chapter 8) advocate that the proposed machine learning techniques represents a significant methodological contribution of this thesis, since these algorithms are successfully employed to implicitly capture the knowledge referring to navigational strategies and to cluster users' trajectories.

This chapter is the last one dedicated to study methodology. The following chapter, the first one among the chapters presenting the study findings, refers to the individual differences related to usability.

Chapter 7

Individual Differences Related to Usability

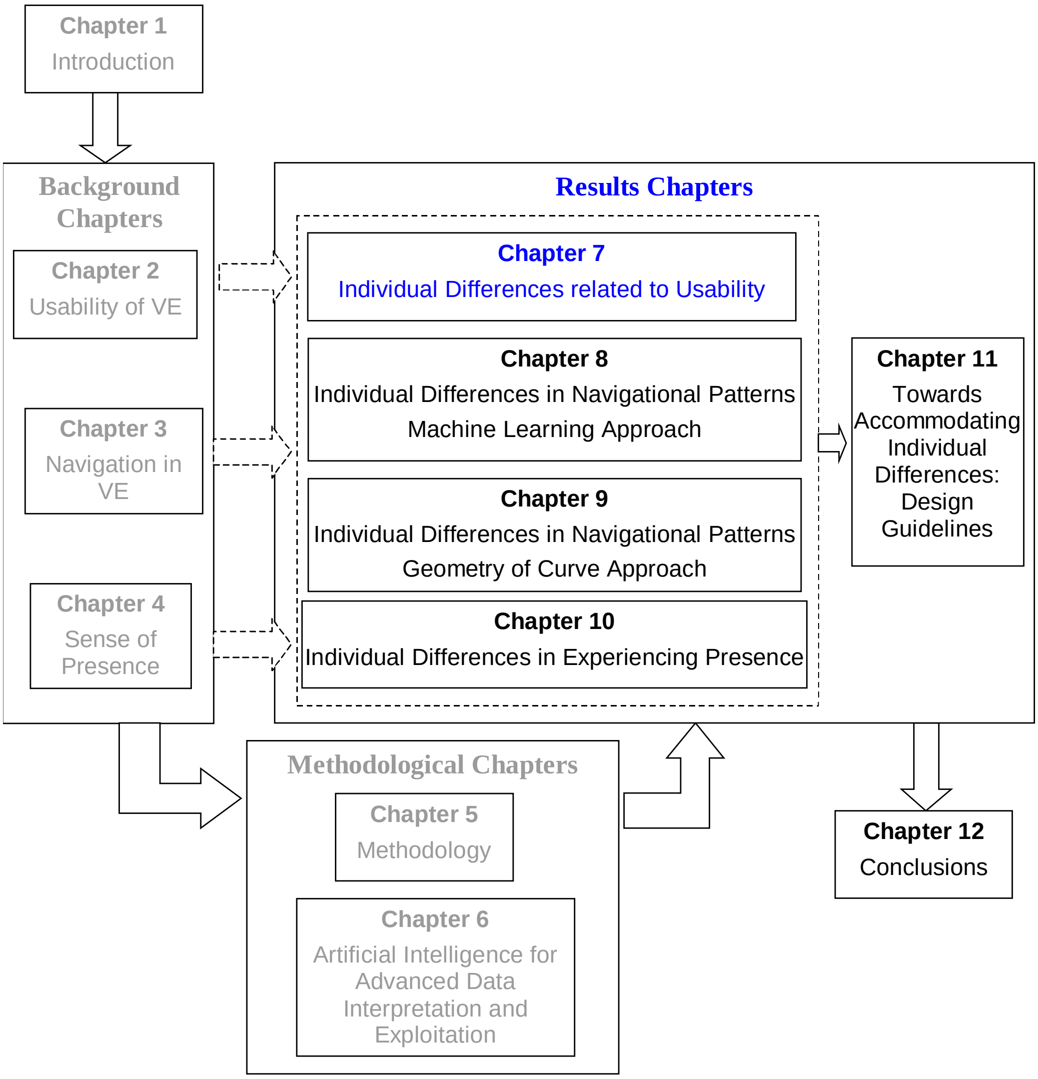


Figure 7.1: Road Map

7.1 Introduction

Until now, the thesis has dealt with providing background and a description of the methodology to be adopted. This chapter, presents results of a study on the impact of individual differences on system usability. The study objective addressed within this chapter focuses on the investigation of individual differences related to system usability. This objective is further detailed in:

- the investigation of the individual differences impacting on performance on spatial tasks, and
- the investigation of the individual differences impacting on the level of satisfaction with the system.

These two objectives delineate the two components involved in assessing usability of any artefact: the level of performance of tasks completed through the use of that artefact, and the level of satisfaction with interacting with that system (see Section 2.2.1).

The performance indicators are usually related to *efficiency* and *effectiveness* (ISO, 1997). In this study, efficiency is considered in terms of resources required to perform the task, while effectiveness is related to the accuracy and completeness of performing the task (see Section 2.2.1). Efficiency has been measured in terms of the time needed to complete the search task, while effectiveness has been assessed through the number of collisions encountered during navigation.

User's satisfaction consists of users' attitude regarding their interaction with the system, and it was measured with a self-rating questionnaire (see Section 5.6.1).

This study design takes the shape of a quasi-experiment, where the quasi independent variables (IVs) can only be statistically, rather than directly manipulated. Thus, participants are assigned to a particular condition because they already qualify for that condition, such as males or females; experts or novices (see Section 5.6). The quasi IVs are users' gender, their previous computer games experience, their personality cognitive style, and the level of sense of presence induced during interaction. By statistical manipulation, it was aimed to investigate the effect of these variables on system usability expressed in terms of task performance and level of satisfaction. These two latter aspects represent the dependent variables (DVs). Several working hypotheses have been formulated, whose theoretical support has been discussed in Chapter 4:

- H1. Males achieve better task performances than females.
- H2. Males experience a higher level of satisfaction in rapport with the VE system.
- H3. The greater the users' computer games experience, the better the task performances.
- H4. The greater the users' computer games experience, the higher the satisfaction in rapport with system usability.
- H5. Sense of presence impacts on task performance.

- H6. Different dimensions of personality cognitive style impact on task performance.
- H7. The greater the presence experienced by the users, the higher their satisfaction.

This chapter focuses on testing these hypotheses, in the light of the objectives outlined above. The description of study results is followed by their discussion.

7.2 Individual Differences Related to Task Performance

In this work, the objective measures of usability (i.e. task performance), consist of time spent on search tasks (see Section 5.4) and the number of collisions encountered during navigation. The variables whose impact on task performance is investigated, are: gender, experience of playing computer games, presence and different dimensions of personality cognitive style. Their relationships with task performance have been thoroughly described in Sections 2.5 and 4.5.

Presence was measured with a questionnaire introduced in Section 5.6.2 and Appendix C. The personality cognitive style was assessed through the Myers-Briggs Type Indicator (MBTI) (Myers and McCaulley, 1998) which measures the strength of preference for the manner of processing information. Its development is grounded on Jung's (1971) theory of personality types, and the four basic dimensions of which are: Extraversion (E)–Introversion (I); Sensing (S)–Intuition (N); Thinking (T)–Feeling (F) and Judging (J)–Perceiving (P) (see Section 5.6.3).

In order to test the impact of these quasi IVs on task performance, several *t*-tests were run, comparing the performance achieved by groups of users, identified on the basis of gender, computer games experience and level of presence.

7.2.1 Gender and Task Performance

Search time

As shown in Table 7.1, the difference is significant at the level 0.05 and suggests that males require significantly shorter time for completing the primed search task.

Table 7.1: *T*-Test Comparing Task Performance in Terms of Search Time Required by Female and Male Users

Variables	Female		Male		
	Mean	SD	Mean	SD	*t*-Test
Search Time	93.33	74.25	60.65	61.57	2.06*

$^{*}p < .05.$ $^{**}p < .01.$

This result is discussed in Section 7.4, where this apparent gender impact on task performance is placed in a larger context. Thus, its relationship with level of expertise, seen as experience of playing computer games, is particularly discussed.

Collisions

The search time was different for each user, according to the accuracy of spatial knowledge acquired during the naive search task. Everything being equal it seems that the longer the time required for the search, the greater the number of collisions. The number of collisions is a function of time, and in order to avoid the confounding of this DV with the search time, it has been replaced with the collision rate. In other words, the number of collisions was considered not in absolute values, but rather scaled by the time factor. Thus, the indicator used in the analysis referred to number of collisions per second. As shown in Table 7.2, the difference is not significant. No gender effect on task accuracy has emerged.

Table 7.2: T-Test Comparing Performance in Terms of Collisions Encountered by Female and Male Users

Variables	Female		Male		
	Mean	SD	Mean	SD	t-Test
Collisions/sec	0.0283	1.40	0.0377	2.41	1.38

$^{*}p < .05.$ $^{**}p < .01.$

7.2.2 Computer Games Experience and Task Performance

Participants in this study have been exposed to computer games on average for seven years. The experts were considered the users with computer games experience greater than seven years, while the novices were the ones with less than seven years experience.

Search time

The difference is significant at the level 0.05 and suggests that users with more than seven years experience of playing computer games required significantly shorter time in order to successfully complete the search task (Table 7.3).

Table 7.3: T-Test Comparing Performance in Terms of Search Time Experienced by Users Grouped on the Basis of their Computer Games Experience

Variables	Group1 (Experts)		Group2 (Novices)		
	Mean	SD	Mean	SD	t-Test
Search Time	35.22	21.78	61.50	32.83	2.10*

$^{*}p < .05.$ $^{**}p < .01.$

Collisions

As shown in Table 7.4, the difference between the collision rate of novice group versus expert group is not significant. Consequently, no conclusion can be formulated with respect to the relationship between the computer games experience and the task performance, expressed as number of collisions per second.

Table 7.4: *T*-Test Comparing Performance in Terms of Collisions Encountered by Users Grouped on the Basis of their Computer Games Experience

Variables	Group1 (Experts)		Group2 (Novices)		
	Mean	SD	Mean	SD	*t*-Test
Collisions/sec	0.0301	1.82	0.0316	1.47	0.22

$^{*}p < .05.$ $^{**}p < .01.$

7.2.3 Presence and Task Performance

Search Time

Pearson's correlations were calculated between presence scores obtained by males and females, and the search times, with alpha set at 0.05. For the female group, the correlation coefficient is statistically significant ($r(12) = 0.82$, $p < 0.01$), indicating a positive relationship between presence and search time, and accordingly, a negative relationship between presence and task performance. Without being statistically significant, the correlation coefficient computed for the male group suggests a positive relationship between presence and task performance ($r(18) = -0.25$, $p > 0.05$).

Two groups of users have been identified, on the basis of their presence scores: those users experiencing a high level of presence (Group 1) and those experiencing a low level of presence (Group 2). The cut off point was the median of presence scores. As shown in Table 7.5, the difference is not significant. However, it suggests that individuals whose presence scores were above the average (Group 1), needed more time for accomplishing the search task.

Table 7.5: *T*-Test Comparing Presence Experienced by Users Grouped on the Basis of the Amount of Time Required for Search Task

Variables	Group 1 (High)		Group2 (Low)		
	Mean	SD	Mean	SD	*t*-Test
Search time	65.18	77.10	60.87	32.38	0.201

$^{*}p < .05.$ $^{**}p < .01.$

Given the apparent significant impact of gender on task performance, expressed as search time, and the relationship it holds with presence, I decided to also investigate their combined impact. ANOVA analysis indicates a significant interaction effect between gender and presence ($F(1,28) = 3.19$, $p < 0.05$).

The increased experience of presence (i.e. above median value), impacts differently on task performance of males and females (Figure 7.2). Females, the more present they experience, the lower their task performance, while for males, the level of presence does not seem to impact on the level of performance.

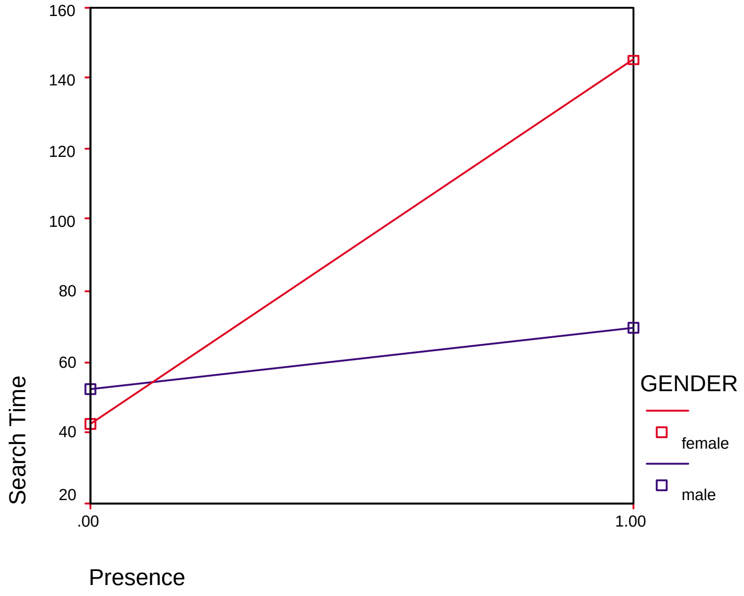


Figure 7.2: Task Performance as a Function of Level of Presence and Subjects' Gender

Collisions

As shown in Table 7.6, the difference is significant at the level 0.05 and suggests that individuals who experienced a high level of sense of presence (Group 1) encountered a greater number of collisions.

Table 7.6: T-Test Comparing Presence Experienced by Users Grouped on the Basis of their Collision Rate

Variables	Group 1 (High)		Group2 (Low)		
	Mean	SD	Mean	SD	t-Test
Collisions/sec	0.0450	0.79	0.0263	1.30	2.41*

$^{*}p < .05$. $^{**}p < .01$.

7.2.4 Cognitive Style and Task Performance

Search time

In order to highlight a possible significant difference and to increase the effect size, three groups of users were considered, on the basis of time needed for the search task. The bottom 20% of users form the group which achieved the lowest performance (Poor Group) in terms of task efficiency. The top 20% of the users are those who required the shortest time for the search task (Good Group). The remaining 60% of the subjects were assigned to the third group (Medium Group). Even if the findings did not show any significant difference between poor and good groups, is seems that the more extrovert or intuitive an individual is, the shorter the time needed to find the library, and accordingly the higher the task performance is (Figure 7.3).

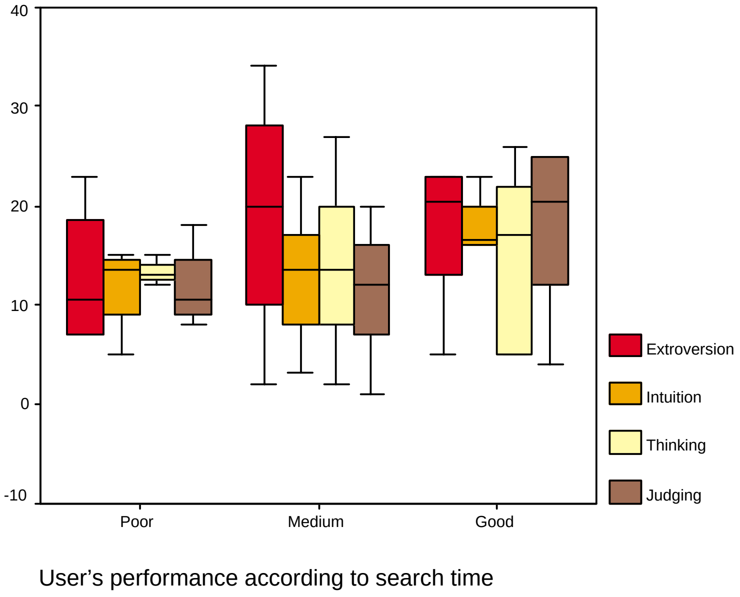


Figure 7.3: The Four Dimensions of Cognitive Style Averaged for Groups of Users Identified on the Basis of Their Collision Rate

Collisions

Two independent groups of users were identified on the basis of the collisions per second, encountered during the search task, and with a cut-off point at the median value. One group generated an above-average number of collisions per time unit, and therefore its users performed worst in terms of task effectiveness, while the other one generated a below average number of collisions per unit which led to higher task efficiency. No statistically significant differences were found along the dimensions of cognitive style, measured within these two groups (Figure 7.4).

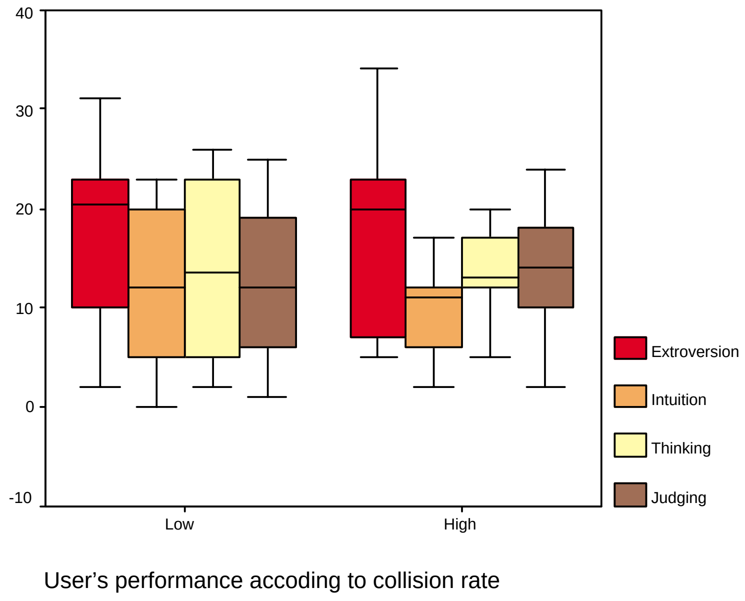


Figure 7.4: The Four Dimensions of Cognitive Style Averaged for Groups of Users Identified on the Basis of Their Collision Rate

Search Time and Collision Rate

In order to reveal the relationship between the two components of task performance: search time and collision rate, Pearson's correlations were calculated between the two variables, separately for male and female groups. For the female group, the correlation coefficient is not significant. It merely suggests a negative relationships between collision rate and the search time. For the male group, the correlation coefficient is statistically significant ($r(19) = 0.51$, $p < 0.05$), indicating a strong positive relationship between collision rate and search time.

7.3 Individual Differences Related to User Satisfaction

In order to test the impact of the quasi IVs on task performance, several *t*-tests were run, comparing the level of satisfaction experiencing by groups of users, identified on the basis of gender, computer games experience and presence.

7.3.1 Gender and Satisfaction

There is a significant gender effect on the level of satisfaction (Table 7.7), with the male group experiencing a significantly higher level of satisfaction regarding the interaction with the system, than the female group.

Table 7.7: T-Test Comparing Satisfaction Experienced by Female and Male Users

Variables	Female		Male		
	Mean	SD	Mean	SD	t-Test
Satisfaction	3.71	0.76	4.22	0.72	2.06*

$^{*}p < .05.$ $^{**}p < .01.$

7.3.2 Computer Games Experience and Satisfaction

As shown in Table 7.8, no conclusion can be formulated with respect to the relationship between the prior computer games experience and the satisfaction experienced by the users.

Table 7.8: T-Test Comparing Performance (search time) Experienced by User Grouped on the Basis of their Computer Games Experience

Variables	Group1 (Experts)		Group2 (Novices)		
	Mean	SD	Mean	SD	t-Test
Satisfaction	4.19	0.98	4.07	0.60	0.39

$^{*}p < .05.$ $^{**}p < .01.$

7.3.3 Presence and Satisfaction

As shown in Table 7.9 there is a significant effect of presence on the satisfaction with the system. The group experiencing more presence (High) (i.e. above median), experienced also a significantly higher level of satisfaction than the other group.

Table 7.9: T-Test Comparing Satisfaction Experienced by User Grouped on the Basis of their Level of Presence

Variables	Group1 (High)		Group2 (Low)		
	Mean	SD	Mean	SD	t-Test
Satisfaction	4.64	0.67	3.95	0.63	2.73*

$^{*}p < .05.$ $^{**}p < .01.$

7.4 Discussion

Findings suggest that the male group required a significantly shorter time in order to carry out the search task than the female group, which appears to validate the hypothesis H1. However, the fact that most of the females are novices while most of the males are experts, suggests that gender and level of expertise are two confounded factors (see Table 7.10).

Table 7.10: Summary of Study Participants Along Two Dimensions: Gender and Length of Playing Computer Games

		Novices	Experts
Males	Count	8	11
	Average length of computer game experience (years)	3.87	12.8
	Average search performance (sec.)	45.00	30.00
Females	Count	11	2
	Average length of computer game experience (years)	0.36	8.5
	Average search performance (sec.)	102.30	33.00

As shown in Table 7.10, expert males (25%) have been in average exposed to computer games for almost 13 years, while novice females (34.37%) have been exposed in average for less than half an year. Therefore, all the conclusions which can be drawn with respect to each of these two factors impacting on task performance, should be cautiously interpreted.

Findings also indicate that the male group experienced a significantly higher level of satisfaction with the system, a fact that validates the hypothesis H2.

The impact of computer games experience on task performance is significant with respect to the time spent on the search task. The expert group performed the search task in significantly less amount of time, as compared to the novice group. The collision rate for the expert group is lower than that of its counterpart. These two outcomes suggest that expert group overtake novices with respect to task performance, validating hypothesis H3. The level of satisfaction experienced by the expert group is higher yet not significantly, compared to the level of satisfaction experienced by novices. Thus, the direction of the relationship as stated in the hypothesis H4 is correct, but the strength of this relationship is not high enough to validate this hypothesis. In an attempt to seek explanation for this result, I analysed the way in which expert and novice groups perceive several system characteristics, such as attractiveness, realism, boredom, exciting, controllable, and demanding. Another significant difference, related to system controllability has been identified ($t(30) = 2.08$, $p < 0.05$). Thus, users previously exposed to computer games considered the system to offer too little control. These subjects did not find the task challenging and did not become motivated enough to perform accurately.

The level of sense of presence experienced by users impacts on both search time and collision rate. Without reaching significance, the findings suggest a negative relationship between presence and task performance, with the latter measured in search time. However, this global impact is different in the case of the male group as compared to female group. For the female group, a statistically significant negative relationship between presence and task performance has been identified, while for the male group, this relationship appears to be very weak. With respect to the impact carried by sense of presence on task accuracy, measured as collision rate, findings indicate a significant relationship: for the users experiencing higher presence, the collision rate was significantly higher. In other words, the more the user acts within the VE in terms of moving, or even bumping into things, the more present one becomes. These outcomes confirm the validity of the hypothesis H5, and suggest a significant degree of complexity in the relationship between presence and task performance.

This complexity has been further explored through personality cognitive style. Another study hypothesis (H6) states that different dimensions of this construct may well impact on task performance. The nature of this relationship, as it appears in the results, is still ambiguous. Cognitive style consists of enduring patterns of organising cognitive processes, and it cannot, on its own, clarify the above-mentioned relationship. This analysis suggests those dimensions that allow users to perform better, given the specific characteristics of the performed task.

Without being significant, the findings indicate that individuals who are more extrovert, intuitive or thinking perform better in terms of task efficiency. Along the Extroversion–Introversion continuum, the extraverted people are predominantly orientated towards the external world, which probably leads to an increased level of spatial awareness.

On the Sensing–Intuition continuum, intuitive people look at the entire picture which emerges from the single parts, but go beyond it. The search task is a complex one and its solution requires information perceived through our senses. However, this does not suffice and the user has to perceive something which is beyond the immediate information. In order to be successful one needs an internal representation of the spatial layout, or a so-called cognitive map. Most likely intuitive individuals are able to take the bird's eye view, as they would see the space from above.

Along the Thinking–Feeling continuum, the thinking type grounds his/her decision on logic and analysis. The need to organise both things and ideas within one's environment could prove beneficial in understanding it. Probably when both extraverted and thinking types are met within the same individual, he/she could achieve higher performance in building up the internal representation of the spatial layout through methodical coverage of space.

Findings indicate a significant effect of presence on the level of satisfaction experienced by the users. Those users experiencing higher level of presence, seem to enjoy more their experience and consequently, to experience a higher level of presence. These results validate hypothesis H7.

7.5 Summary

This chapter investigated individual differences related to system usability. With respect to gender differences, the female group appear to accomplish the search task in a significantly longer time and consequently experienced a reduced level of satisfaction in interacting with the system. However, given the confounded variables such as gender and level of expertise characterising participants in this study, this outcome should be carefully interpreted. These identified gender-related differences are likely to reflect differences between expert and novice groups. Therefore, further work should be carried out to identify the distinct impact of gender and level of expertise on spatial performance.

With respect to the impact of computer game experience on task performance, the results of the expert group differ significantly from those of the novices, in terms of the time needed to accomplish the search task, but not in the collision rate. In other words, prior experience impacts on efficiency but not on effectiveness. An explanation for this result may be that the previous exposure to computer games shaped users' expectations. Expert users complain about lack of control, and since the tasks were not challenging enough to motivate an adequate level of cognitive load, their performance lacked accuracy.

The relationship between presence and task performance proved again to be difficult to establish, suggesting that it should be considered in the broader context of task characteristics and user gender. Attempts to understand this relationship should come from various perspectives. Personality cognitive style seems to be a promising direction to follow for revealing some of these interdependencies (see Section 10.5). The relative limited sample size, did not allow a proper analysis, since the users' dispersion along each of the bi-polar dimensions of personality cognitive style was quite large. Future work will continue this line of research.

The results presented merely suggest some trends, and they do not indicate causal relationships between the investigated variables and task performance. Due to the task characteristics (e.g. navigation), it is likely that extraneous variables, such as spatial ability could be found responsible for the identified gender-based differences or maybe even for the impact of presence on task performance. Probably, the better the users' set of abilities match the task requirements, the easiness of performing brings enjoyment and eventually a higher level of presence.

Some valuable lessons can be learned with respect to the design of VEs, for accommodating such individual differences (see Chapter 11).

The next two chapters focus on the individual differences related to navigational tasks. Each of these chapters presents an original methodological approach for performing such an investigation.

Chapter 8

Individual Differences in Navigational Patterns — A Machine Learning Approach

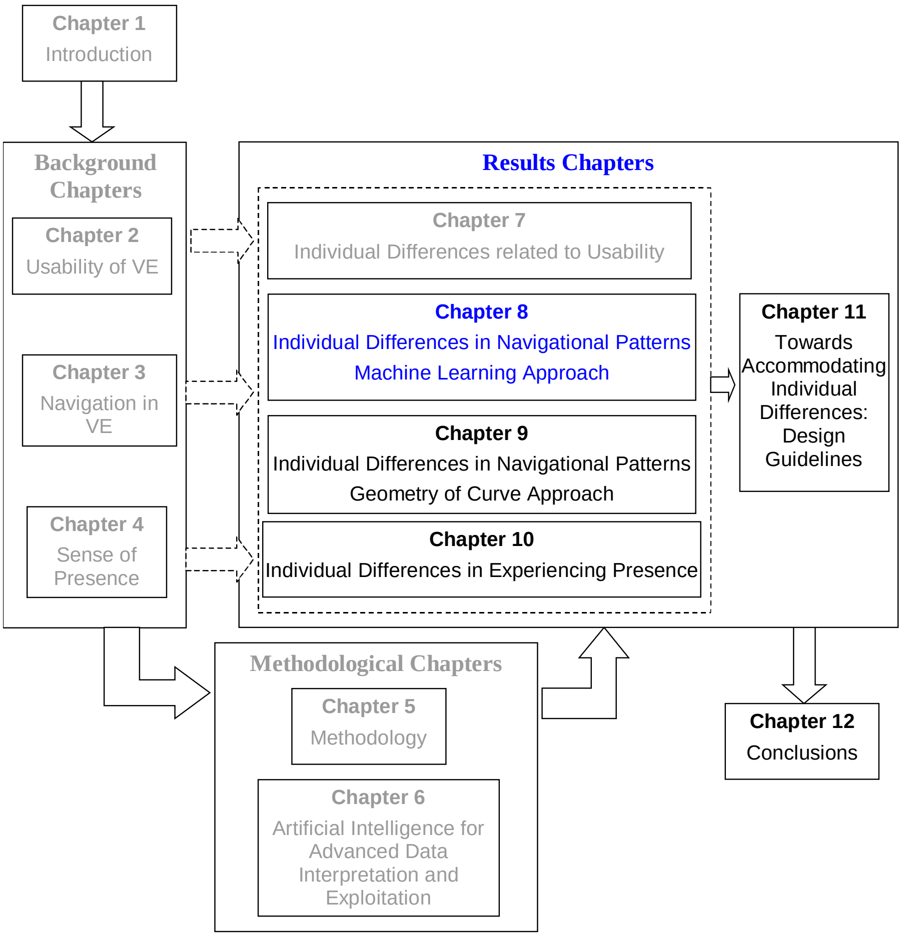


Figure 8.1: Road Map

8.1 Introduction

A major theme of this thesis focuses on understanding how people explore an indoor virtual space. Given the transfer of skills from real to the virtual world (Waller, 2000), this investigation can additionally enrich the understanding of human spatial behaviour in the physical world. Such an understanding can provide theoretical contributions, which should be seen in the larger theoretical framework described in Chapter 3, and can also be harnessed within practical applications. Designing flexible Virtual Environments (VEs), able to adapt themselves in order to support user navigation is one of the most promising application fields. Designing adaptive VEs for navigation support implies ensuring their sensitivity to different types of users (see Sections 2.6.1 and 5.9). Such adaptive VEs should be able to discriminate between different groups of users, who require different accommodations. These groups of users differ not only in their performance on spatial tasks, but also in their spatial behaviour. Another significant aspect towards designing adaptive VEs for navigation support consists of identifying ways to accommodate individual differences in navigational patterns.

This chapter focuses on the analysis of users' spatial behaviour, as reflected in their trajectory paths. Movement paths allow an online and unobtrusive identification of user groups. Trajectory classification presents an appealing potential for performing such kind of identification. The analysis of movement paths also allows the implicit extraction of navigational patterns embedded in trajectory paths. Such patterns are part of user mental model of navigation which can be exploited to support low spatial users (see Chapter 11). This chapter addresses the following three objectives, introduced in Section 1.3:

- The investigation of the individual differences in navigational patterns followed by users within the VE,
- The implicit and real time discrimination of low-high spatial users through on-line trajectory classification, and
- The investigation of the rules and strategies underlying user spatial behaviour and the development of a user model based upon them.

I conjecture that different search styles, strategies and rules, which are hidden in navigational patterns, can emerge from such an analysis. Attempts to validate this hypothesis require a novel methodology. Traditional techniques for knowledge elicitation present a series of limitations, particularly when it comes to extract implicit knowledge, inherently associated with navigational rules or strategies (see Section 3.2.4). Because of their sensitivity to learning temporal sequences, connectionist models, and in particular Recurrent Neural Networks (RNNs) are particularly suitable for extracting such rules (Elman, 1990; Ellis and Humphreys, 1999; Ghiselli-Crippa, 2000). The richness and accuracy of the quantitative data recording participants' spatial behaviours support this methodological approach (see Section 5.8).

In order to address the outlined objectives, this chapter is organised along two main topics: trajectory classification and trajectory prediction. Trajectory classification allows the analysis of users' spatial behaviour, in order to identify different groups of users, whose needs should be differently accommodated. Trajectory prediction exploits the potential of connectionism models, and in particular of RNNs for implicitly capturing navigational rules (see Section 3.2.4). The analysis of the results of trajectory prediction was performed by clustering best predictions, and by applying the rule induction algorithm on the obtained clusters.

8.2 Clustering Trajectories

Studies in the area of spatial cognition were concerned with testing hypotheses about the impact of various navigational cues, or ways to provide navigational cues (Waller, 2000; Darken and Banker, 1998; Darken and Sibert, 1996a), on spatial knowledge acquisition (see Section 3.3.3). However, none of these studies have tried to investigate holistically the motion trajectories. In this thesis, such an analysis focuses on identifying efficient versus inefficient behavioural patterns and their associated characteristics.

By providing a rich set of primary data, trajectory analysis can support the extraction of valuable information regarding the rules users employ in accomplishing spatial tasks. Moreover, when this analysis is performed in the light of some performance criterion (e.g., time required to perform a search task) it can provide valuable insights into discriminating efficient and inefficient navigational strategies and clustering the users accordingly.

Trajectory classification provides the benefits of reducing the huge amount of information stored in raw data and once a typology has been created it can be used to assess any new trajectory by comparing and assigning it to the appropriate class. Online trajectory classification would allow the identification of user's in terms of good or poor performers of spatial tasks. This identification could represent an essential initial step in designing the adaptive VE. Thus, the VE could be dynamically reconfigured in order to enable poor users to learn the efficient navigation procedures, while for good performers, it can be redesigned in order to challenge users' spatial skills.

Attempts to cluster trajectories have been carried out primarily in the area of visual surveillance, especially novelty detection, with the purpose of identifying suspicious behaviour of pedestrians within an outdoor open area (Grimson et al., 1998; Owens and Hunter, 2000). This goal was directly linked to the idea of automatic surveillance, which would allow the replacement of human operator. In their study, Owens and Hunter (2000) have shown that the Self-Organising Feature Map (SOM) can be successfully employed to perform trajectory analysis. It allows the identification of normal trajectory characteristics and the detection of novel, unusual trajectories. Thus, without underestimating the role of traditional clustering methods, this thesis proposes the use of Artificial Neural Networks (ANNs) as an alternative tool for trajectory classification.

8.2.1 Cluster Analysis Performed by Artificial Neural Networks

The main goal of cluster analysis is to reduce the amount of data, by subdividing a set of objects into (hierarchical arrangement of) homogeneous subgroups. Reducing complexity without loss of information allows better understanding of the analysed data (Lorr, 1983).

An important aspect of any clustering method is the minimisation of classification errors. As Kaski (1997) pointed out, a problem usually associated with clustering methods is cluster interpretation. Due to its ability to extract patterns and to visualise complex data in a two-dimensional form (Kaski, 1997), a SOM (see Section 6.3.1) was used to perform the trajectory cluster analysis. Like many other clustering techniques, SOM reduces representations to the most relevant dimensions, with minimum loss of knowledge about their interrelationships (Kaski, 1997).

The SOM is a neural network algorithm with several advantages over other clustering techniques (Kaski, 1997; Owens and Hunter, 2000). The mapping from a high dimensional data space onto a two-dimensional output map is effectively used to visualise metric ordering relations of input data. Reducing the amount of data allows comprehensible cluster identification and interpretation, which is difficult in the case of traditional clustering methods (Kaski, 1997). As with any other ANNs, SOM has a considerable potential to generalise. Once it is trained, SOM is able to classify new data within the set of clusters previously identified.

Features like the approximation of the probability density function of the input space, the identification of prototype best describing the data, the visualisation of the data and, the potential to generalise highly recommend SOM for on-line automatic extraction of trajectory clusters.

Learning Vector Quantisation (LVQ) (Kohonen et al., 1995) is a supervised learning algorithm related to SOM (see Section 6.4.4). The SOM and LVQ algorithms have been developed by Teuvo Kohonen and implemented by his team from Helsinki University of Technology, in the form of SOM_pak (Kohonen et al., 1996) and LVQ_pak (Kohonen et al., 1995). These comprehensive software package are available online and were used in this thesis. SOM is based on an unsupervised learning process, allowing both the cluster identification within the input data and the mapping of an unknown — not previously seen — data vector onto one of the clusters. This process is carried out without any prior knowledge regarding the number and content of clusters to be obtained (Kaski, 1997). When a set of already clustered input data is available, a supervised learning process, for example LVQ can be employed to identify to which class an unknown data vector belongs. For a detailed description of SOM and LVQ see Sections 6.3.1 and 6.4.4.

The use of SOM (Kohonen et al., 1996) and LVQ (Kohonen et al., 1995) for performing the trajectory cluster analysis requires several steps: data collection, construction and normalisation of data set, unsupervised training, visualisation of the resulting map, cluster identification, obtaining a set of trained labelled codebook vectors to be used in supervised training and measuring classification accuracy. When all these steps are performed in order to classify online trajectories, they should be automatic and seamlessly interconnected. For this, several modules were developed, serially connected as presented in Figure 8.2.

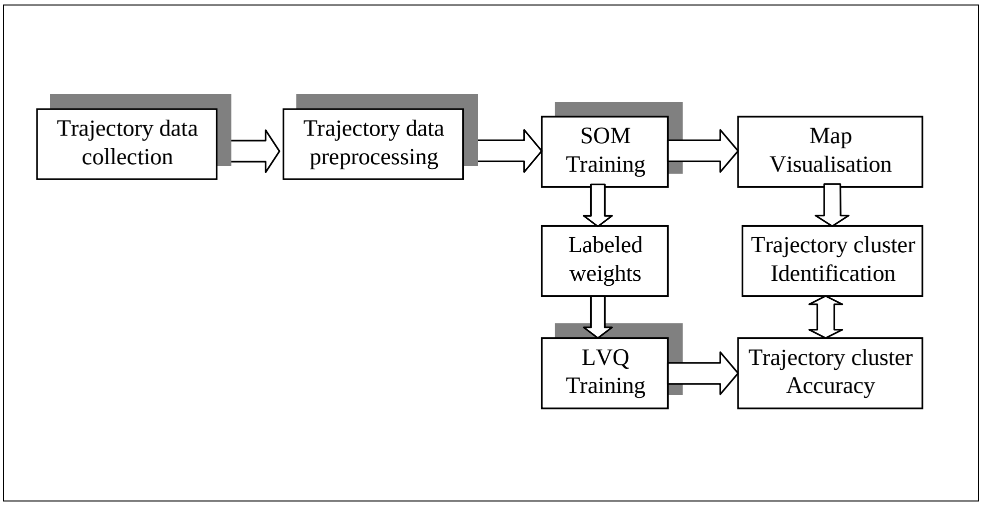


Figure 8.2: Modular System for On-line Trajectory Classification

8.2.2 Collecting Data

The data collection module is based on the listener agent developed by Delahunty (2001) (see Sections 5.8 and 11.4.6). This agent gathers information about user behaviour within the virtual world. The data captured when the user interacts with the ECHOES virtual space contains details of navigation paths through the world and time spent in different rooms (see Section 5.8).

8.2.3 Pre-Processing Data

Data pre-processing consisted of transformation of the raw data into a suitable form to be fed into the SOM. In the raw data, each trajectory is represented by a multivariate time series. Testing if the static representations of trajectories are sufficient to perform their classification, involved reducing the raw data by preserving its significant features.

I choose to represent each trajectory by the degree of occupancy of a predefined set of spatial locations. For the SOM analysis, the virtual space was overlaid with a grid composed of 28 squares of 4×4 virtual metres. Each trajectory was converted to a succession of locations on the grid. The next step necessitated the mapping of each trajectory into a sequence of 28 neurons (one for each location), according to the equation 8.1, where NV is the input node value and LOC is location occupancy expressed in number of times the user revisited that location.

$$NV = \log_{10}(9 \cdot LOC + 1). \tag{8.1}$$

The above transformation allows a clear differentiation between non-visited locations, for which NV = 0, and visited locations. In the later case, the NV is within the range 1–2, 1 staying for only one visit and 2 for 11 visits, 11 being the maximum number of times of revisiting a location.

Apart from this encoding which features the space covering, the trajectories were also characterised by the amount and size of users' rotations. An additional input node, 29th node, represents the degree of rotating in VE. It is considered that trajectories characterised by rotation angles greater than 90 deg present an interesting feature which deserves special attention. If a trajectory has more than 10% of the rotation angles equal or greater than 90 deg, the 29th node of the input vector was set to 3, otherwise it was set to 0.

8.2.4 Training SOM

Once the trajectory data was pre-processed, it was randomly divided in two equal subsets. One set of data has been used for training, while the other one was kept for testing. Each set consisted of 63 vectors, comprising the encoded trajectories covered by users on each level.

A SOM of 16×12 neurons was used to perform a topology-preserving mapping. The first phase of training was carried out for 1000 epochs, with a radius of 16 and with a learning rate of 0.8. The second phase lasted for 120 000 epochs, with a learning rate of 0.01 and a radius of 2. The random seed of 275 was identified by using the *vfind program*. These parameters were retained, after more than 100 trainings were tried, with different architectures and learning rates. This set of parameters led to the smallest *quantisation error* for the testing set (1.97), while for training set it was 0.35. Quantisation error represents the norm of difference of an input vector from the closest reference vector (Kohonen et al., 1996).

8.2.5 Map Visualisation

The resulting organisation of the map, shown in Figures 8.3 and 8.4, suggests five clusters of trajectories. Figure 8.3 is associated with the training set of trajectories, while Figure 8.4 is associated with the testing set. The initial numbers which represent the winner neurons within each cluster were replaced by the trajectory corresponding to each winner node.

SOM provides an additional benefit with respect to map visualisation. Lighter colours indicate higher similarities between the winner nodes, while darker shades of grey imply greater dissimilarities. This offers an intuitive understanding of clusters' boundaries (Kohonen, 2001).

8.2.6 Cluster Identification

Training the SOM led to five clusters. In referring to them, a number has been assigned to each cluster, which is placed on the map, in the area corresponding to that cluster.

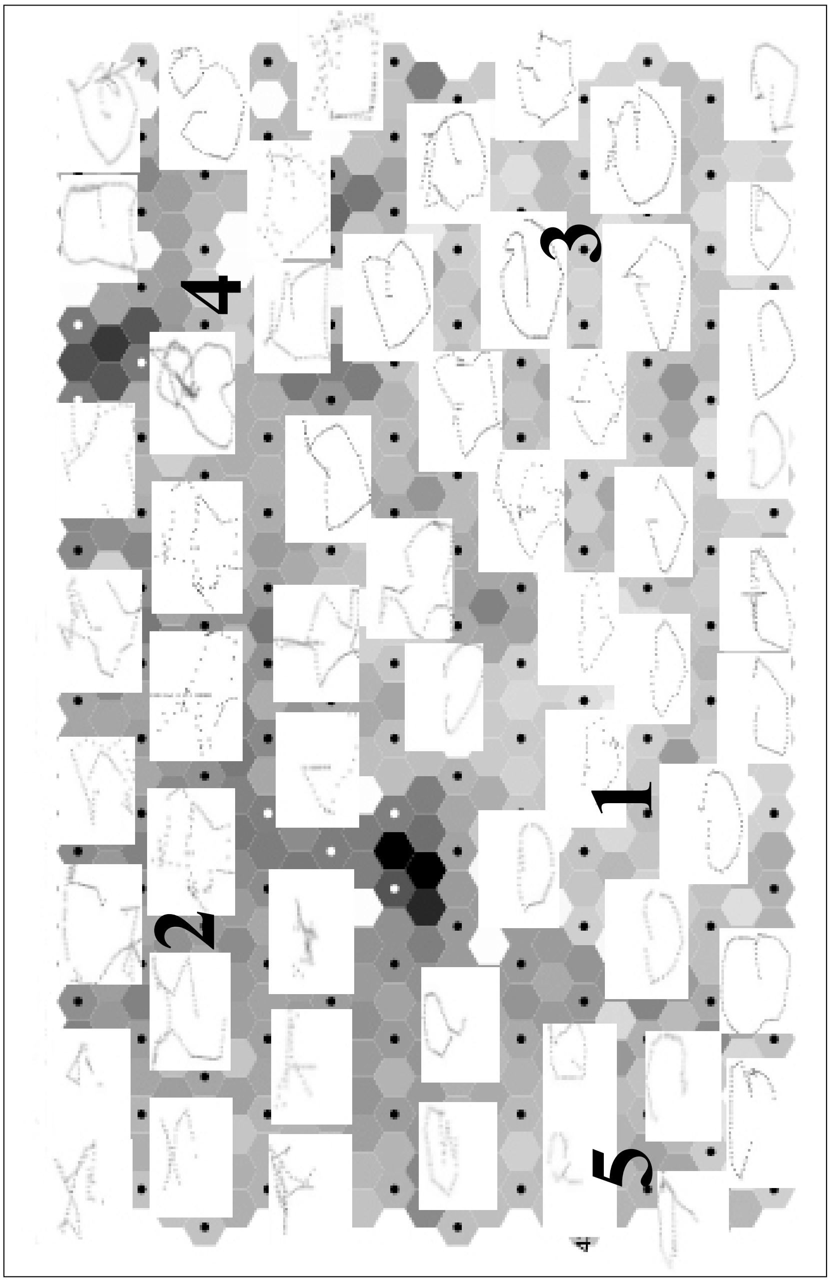


Figure 8.3: The resulting organisation of the SOM map obtained through clustering trajectories from the training set. Each winner neuron on the map was replaced by a plot of the corresponding trajectory, while the numbers from 1 to 5 represent trajectory clusters.

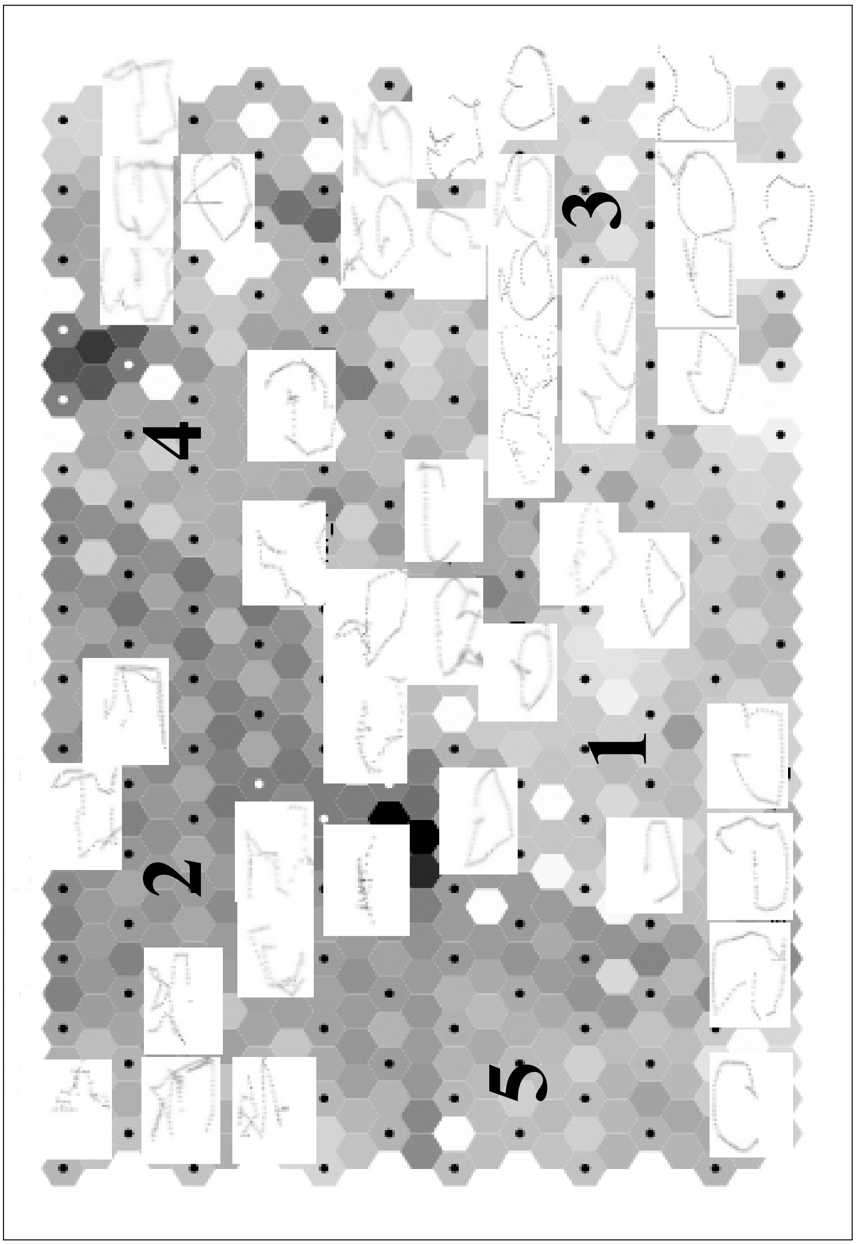


Figure 8.4: The result SOM map obtained through testing its initial organisation with trajectories from the testing set. The white boxes represent individual trajectories from the testing set.

For instance, cluster number 1 comprises the trajectories within area designated by number 1, located in the middle of the lower half of the map.

Cluster 1 groups trajectories limited to the lower half of the spatial layout, such as the two smaller rooms. These trajectories are generally circular. Some of these trajectories are smooth while others present sharper angles.

Cluster 2 located on the top left of the map comprises trajectories which present lots of turnings and crossovers. These trajectories are completely different than any other group, containing straight lines joined at sharp angles. They do not allow an efficient coverage of the space, are more likely to induce disorientation and accordingly, the level of spatial knowledge which can be acquired through them is limited. As can be seen, there are two sub-clusters that can be identified within this class, whose main distinction resides in the coverage of the space. For some of trajectories, the coverage is restricted to only one room of the space, while the rest of them cover larger space, but rarely going circular. Actually these trajectories are erratic and the user seems anxious to explore the space, for example he/she rather moves in the same area or covers larger space but in this case, it is likely that returning to the starting point is achieved through approximately the same path.

Cluster 3 located on the right part of the second half of the map, consists of very smooth circular trajectories, which have at least one direction towards the centre of the spatial layout.

Cluster 4 comprises longer trajectories, which cover most of the spatial layout. They present the "going around the edge" feature, more pronounced than other clusters.

Cluster 5 presents trajectories performed within the larger room of the spatial layout. They are usually circular trajectories.

Each set of trajectories, with the exception of Cluster 2, can prove beneficial for acquiring spatial information. Carefully selected and ordered, they enable users to acquire particular spatial knowledge, with minimum investment of resources.

Previous work in classifying trajectories, performed only on the basis of location occupancy without accounting for the rotation behaviour, led to a more detailed classification (Sas et al., 2002). However, since one of the purposes of this thesis is to discriminate between users employing efficient strategies and those navigating through a set of inefficient strategies, the rotation angle has to be also taken into account. This leads to a more detailed representation of Cluster 2.

8.2.7 Training LVQ

Once the SOM was trained, the codebook vectors could be used for initialising the weights for LVQ algorithm. This led to increased classification accuracy of 87%, compared to only 72% obtained using random initialisation. In other words, each trajectory from the testing set was correctly classified by the LVQ with 87% accuracy. Within each class, the classification accuracy is slightly different: cluster 1 — 86%, cluster 2 — 100%, cluster 3 — 63%, cluster 4 — 87% and cluster 5 — 100%. As can be seen, the trajectories belonging to Cluster 2 which requires special attention are correctly classified in each case. The increased interest in this cluster, is given by the fact that more than 50% of its trajectories are followed by the subjects with worst performance in the search tasks. In other words, Cluster 2 provides an interesting benefit by bounding users' spatial behaviours — movement paths — with their spatial abilities (e.g. performance on search tasks). This is an important outcome, supporting the goal of this study aiming to discriminate users in terms of good and poor performers of the spatial tasks.

8.2.8 Conclusions

These findings suggest that ANNs can be successfully employed in modelling spatial behaviour in VE, in terms of classifying users' on-line trajectories. Based on this classification, each new user can be assigned to one of the clusters, and accordingly identified as employing efficient or inefficient navigational strategies.

The SOM and LVQ analysis led to the identification of five users' trajectory clusters. The accuracy of classification above 85% is a significant outcome given the relatively limited size of the training and testing sets. Within each cluster, trajectories share common features. Some of them were already identified while the others request further analysis.

All clusters except one could prove beneficial for the performance of the search task. Special attention was paid to Cluster 2 which consists of erratic trajectories, presenting lots of turns and straight line segments joined at sharp angles. Since more than 50% of trajectories composing Cluster 2 belong to the subjects with the worst performance on the search task, the trajectories within this cluster are considered *poor* trajectories. Two examples of such trajectories are presented in Figures 8.5 and 8.6. For illustration, two examples of *good* trajectories are also presented in Figures 8.7 and 8.8.

After discriminating between poor and good navigators, an adaptive VE should be able to tailor itself to users' needs, such as providing navigation support to low spatial users (see Chapter 11). This aim can be achieved only by building a user model of navigation, consisting of users' navigational rules and strategies (see Section 11.4.3). A comparative analysis of efficient versus inefficient rules provides a basis for selecting what should be accommodated and in which way. A major obstacle in extracting these rules is related to their implicit nature and resides in the limitations of traditional

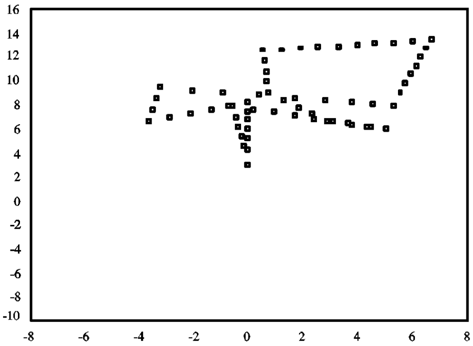


Figure 8.5: Poor Trajectory 1

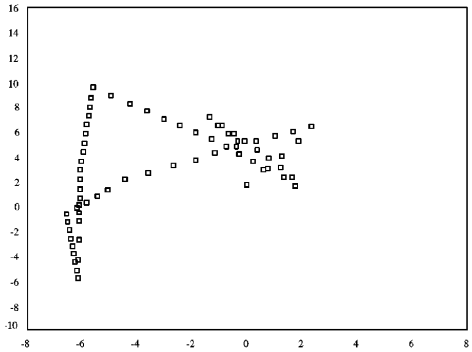


Figure 8.6: Poor Trajectory 2

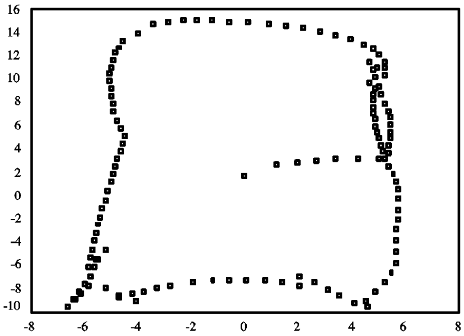


Figure 8.7: Good Trajectory 1

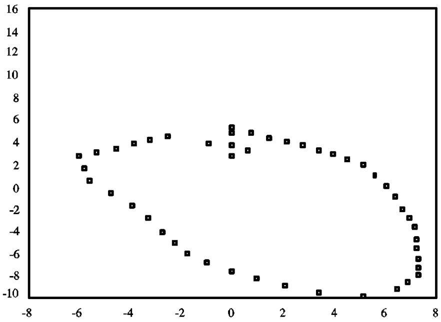


Figure 8.8: Good Trajectory 2

techniques for knowledge elicitation (see Section 3.2.4).

Neural networks provide a very powerful toolbox for modelling complex non-linear processes in high dimensionalities (Lint et al., 2002). ANNs have many advantages over the traditional representational models, particularly in terms of distributed representations, parallel processing, robustness to noise or degradation and biological plausibility (Haykin, 1994). It is consider that at least part of these strengths can be harnessed to model user's spatial behaviour. Because of their sensitivity to learning temporal sequences, Recurrent Neural Networks (RNNs) are particularly suitable for extracting such rules (Elman, 1990; Ellis and Humphreys, 1999; Ghiselli-Crippa, 2000).

8.3 Trajectory Prediction

Human motion analysis and in particular trajectory prediction is one of the key areas in computer vision for many applications including visual surveillance (Johnson and Hogg, 1996; Grimson et al., 1998; Owens and Hunter, 2000), mobility management for Asynchronous Transfer Mode (ATM) networks (Liu et al., 1998) or biomedical sequence understanding (Psarrou and Buxton, 1993).

The motivation for designing a model for predicting users' trajectory is twofold. Firstly, this will offer a better understanding of user spatial behaviour, especially in terms of navigational strategies, since it consists of an indirect method to highlight the users' spatial representations. Extracting knowledge from the trained RNN, which learned to predict the users' trajectory, allows the exploration of regularities, implicitly embedded into the trajectory path, which can be expressed in terms of rules governing the spatial behaviour. As Psarrou (1994) stressed, since users move purposely in an environment,

> the effective prediction on their trajectories can be achieved by modelling the spatio-temporal regularities associated with their moving purposes. Such hidden regularities can be represented by a finite state machine where the location of the regularities correspond to the states of the machine and the orientation and displacement vectors correspond to the transition arcs. Such a representation can be modelled on a neural network based on Elman's architecture that learns the significant locations of the trajectory of a moving object and encodes such information in its hidden units.

The second reason for developing a trajectory prediction module is that the quality of interaction, a cornerstone of the usability of VEs, can only be enhanced if the system is able to dynamically reconfigure/adjust itself in order to meet individual differences across a wide range of users. The accuracy of a user's path prediction determines the accuracy of the implemented strategies which are meant to challenge, capitalise or compensate users' knowledge and skills (Chen et al., 2000) (see Section 2.6.3).

A simple RNN (Elman, 1990, 1991) has feedback which embodies short-term memory. This makes it suitable for application to symbolic tasks that have a sequential nature. Such a network is able to recognise sequences and also to produce short continuations of known sequences.

Previous studies have shown that RNNs can predict both circular and figure eight trajectories (Elman, 1990; Hagner et al., 1999; Pearlmutter, 1989; Psarrou and Buxton, 1994; Psarrou et al., 1995; Sundareshan et al., 1999). Such studies have been particularly interested in exploring the computational power of RNNs and their suitability for trajectory prediction task. Findings suggest that given the fact that the figure eight trajectory crosses itself, the training was more difficult for this type of trajectory. In this thesis, the trajectories covered by users are more complex than a circle or figure eight, even though some of them resemble a circular shape. In addition, trajectory prediction is employed not as an end, but as a means for the purpose of symbolic rule extraction. The Trajectory Prediction module involves a set of steps which are presented in Figure 8.9. Each of these steps is further described.

8.3.1 Collecting Data

The data collection module is the same as the one described in Section 8.2, for the purpose of trajectory classification. It is based on an listener agent which gathers information about user spatial behaviour within the virtual world (Delahunty, 2001) (see Sections 5.8 and 11.4.6).

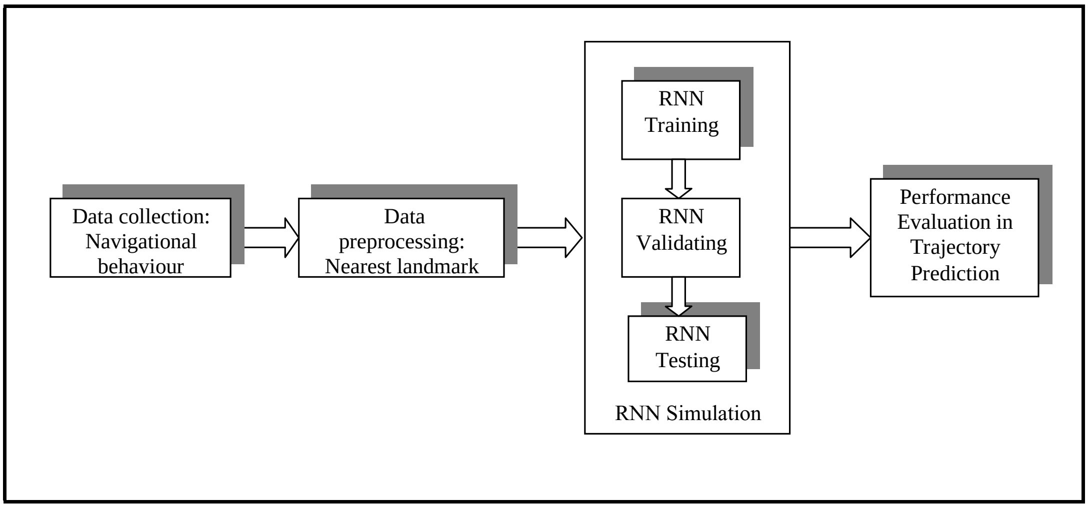


Figure 8.9: Modular System for Trajectory Prediction

8.3.2 Pre-Processing Data

Before preparing data in a suitable format to train the RNN, the elements to be input have to be chosen. The basic content to be given to the RNN, as described in Section 3.2.2 presents twofold requirements. On one hand, such elements should provide sufficient information, possibly slightly redundant, for encoding various aspects of spatial behaviour. Therefore, the selected information refers to user's absolute location, user's relative location with respect to the surrounding area, and user's heading. On the other hand, the chosen input elements should be economically expressed, given the relatively limited size of the data.

Since the RNN will be trained with user's position and heading, distance to the nearest landmark and its centre, and the level where the trajectory has been covered, data pre-processing module includes primarily a series of algorithms for computing the distances to the landmarks.

Using the overhead map for each floor of the virtual building, a visual inspection of the set of landmarks furnishing the interior of the VE has been performed. This analysis led to three distinct classes of landmarks according to their shapes: rectangle, ellipse or segment.

Landmarks whose shape was approximated with a RECTANGLE, such as sofas, desks, tables, and chairs are the most frequent. The landmarks in the shape of SEGMENT usually are the ones which have a very narrow width, such as screens, paintings or boards. Passages such as doors or the entrance to the virtual lift are considered SEGMENT landmarks as well. Landmarks whose shape was approximated with an ELLIPSE or a CIRCLE are encountered seldom in the VE, such as the table in the meeting room and cactus located on the lobby room.

The distance to the nearest landmark has been obtained by computing the distance to each landmark within the room, where the user was currently located (see Algorithm 3).

Algorithm 3 Distance to the nearest landmark

```
Require: User position, in terms of (x, y) coordinates
    Landmark type: rectangle, ellipse, segment
    Landmark coordinates: corners, length of the axes, end points, centres
Ensure: The computation of the shortest distance to the nearest landmark
Identify user's current level {Locating the user}
Identify user's current room
for all landmarks j in the current room {Identify its type and compute distance to it} do
  if landmarktype = RECTANGLE then
    Call the method (Algorithm 4)
  else if landmarktype = SEGMENT then
    Call the method (Algorithm 5)
  else if landmarktype = ELLIPSE then
    Call the method (Algorithm 6)
  end if
end for
Distmin = dist[1] {Initialisation with the distance to landmark number 1}
for all landmarks j in the current room {Identify the nearest one} do
  if Distmin $\geq$ dist[j] then
    Distmin = dist[j]
    landmarknumber = j
  end if
end for
landmark.type = landmarktype
landmark.distance = Distmin
landmark.centre.x = landmarkcentre.x
landmark.centre.y = landmarkcentre.y
return landmark
```

Due to the specifics of ECHOES system, which offers a cluttered environment populated with a large set of landmarks of different shapes and sizes, a very accurate computation of these distances was necessary. The straight forward solution of computing the distance between user location and the centre of each landmark was considered inappropriate. It involves the risk of confounding closely located landmarks, particularly when they have different sizes. Therefore, these distance have been computed from user position to each point of the object contour, or to each of its corners and edges.

Different algorithms have been employed for each type of landmarks. The shortest distance to a landmark in a shape of rectangle (Figure 8.10) is computed according to Algorithm 4.

The shortest distance to a landmark in a shape of segment (Figure 8.11) is computed according to Algorithm 5.

Computing the distance to the nearest landmark in the shape of ellipse or circle as a particular case, involved a more elaborated approach. The parametric equation

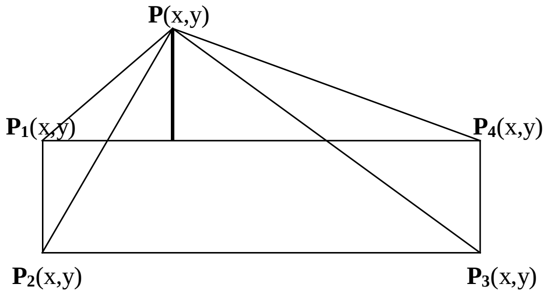


Figure 8.10: Shortest Distance to the Landmark in the Shape of Rectangle

Algorithm 4 Shortest distance to the landmark in the shape of RECTANGLE

```
Require: User position, in terms of (x, y) coordinates
    Landmark coordinate: four corners, centre
Ensure: The computation of the shortest distance to the landmark in the shape of RECTANGLE
for all corners $i = 0$ to 3 {distance to each corner} do
    $distcorner[i] = ((position.x - corner[i].x)^2 + (position.y - corner[i].y)^2)^{1/2}$
end for
Order the distances to the corners in the descending order: the nearest corner[1], the furthest corner[4]
Call the method Distance to SEGMENT {Compute the distance (distrectside12) to the segment whose ends are the first two nearest corners: corner[1], corner[2]}
Call the method Distance to SEGMENT {Compute the distance (distrectside13) to the segment whose ends are the first and the third nearest corners: corner[1], corner[3], especially for the case of long rectangle landmarks (Figure 8.10)}
if The foot of the perpendicular on the segment generated by corner[1] and corner[2] belongs to this segment then
    Distminrectangle = distrectside12
else if The foot of the perpendicular on the segment generated by corner[1] and corner[3] belongs to this segment then
    Distminrectangle = distrectside13
else
    Distminrectangle = distcorner[1]
end if
Return Distminrectangle
```

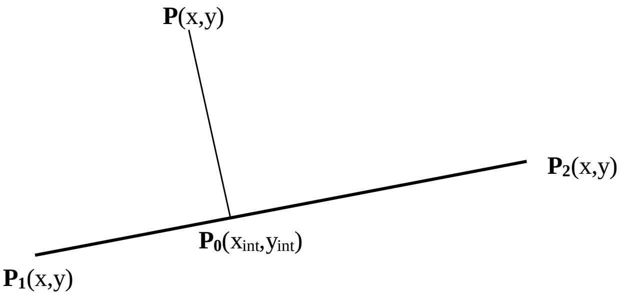


Figure 8.11: Shortest Distance to the Landmark in the Shape of Segment

Algorithm 5 Shortest distance to the landmark in the shape of SEGMENT

```
Require: User position, in terms of (x, y) coordinates
    Landmark coordinate: two endpoints, centre
Ensure: The computation of the shortest distance to the landmark in the shape of SEGMENT
for all ends $i = 0$ to 1 {distance to each end} do
    $distend[i] = ((position.x - end[i].x)^2 + (position.y - end[i].y)^2)^{1/2}$
end for
Order the distances to the ends in the descending order: the nearest end[0], the furthest end[1]
$a = end[1].y - end[0].y$
$b = end[0].x - end[1].x$
$c = end[0].y \cdot (end[1].x - end[0].x) - end[0].x \cdot (end[1].y - end[0].y)$
$d = position.y \cdot a - position.x \cdot b$
$x\_int = -(c \cdot a + b \cdot d)/(a^2 + b^2)$
$y\_int = (d \cdot a - b \cdot c)/(a^2 + b^2)$
$Distsegment = ((x\_int - position.x)^2 + (y\_int - position.y)^2))^{1/2}$ {Compute the distance to the segment}
if The foot of the perpendicular on the segment belongs to this segment then
    Distminsegment = Distsegment
else if The foot of the perpendicular on the segment does not belong to this segment then
    Distminsegment = distend[0]
end if
Return Distminsegment
```

describing an ellipse is given by the equations 8.2 (Gray, 1998):

$$\begin{aligned} x(t) &= a \cdot \cos(t) + x_0 \\ y(t) &= b \cdot \sin(t) + y_0, \end{aligned} \tag{8.2}$$

where a and b are the length of the major and minor axis respectively, and t is the parameter ($0 \leq t < 2\pi$). The distance from the current position P(x,y) to the ellipse is:

$$Distellipse(t) = ((a \cdot \cos(t) + x_0 - x_1)^2 + (b \cdot \sin(t) + y_0 - y_1)^2)^{1/2} \tag{8.3}$$

The minimum distance to the ellipse (Figure 8.12) is given on the point of the ellipse, defined by the parameter t, which is the solution of the first derivative of the distance to the ellipse.

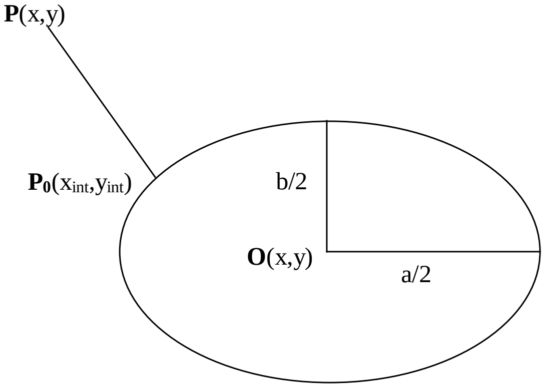


Figure 8.12: Shortest Distance to the Landmark in the Shape of Ellipse

Therefore the equation 8.4 has to be solved.

$$Distellipse(t)' = 0 \tag{8.4}$$

Solving the equation 8.4, leads to a quartic equation 8.5:

$$-a^4 \cdot P + a^3 \cdot (-2 \cdot M + 2 \cdot N) + a \cdot (2 \cdot M + 2 \cdot N) + P = 0, \tag{8.5}$$

where the solution $a = \tan(t/2)$. The parameters of the equation 8.5 are given by the Algorithm 6.

Apart from the algorithms previously described, data pre-processing module involves also the normalisation of the raw data (between -1 and 1) and their preparation in a suitable format required by the SNNS simulator (Zell et al., 1995).

8.3.3 Training RNN

An Elman (1990) simple RNN was used to learn the trajectory and to predict the next step. The reason motivating the choice of this type of ANN is detailed in Sections 3.2.4

Algorithm 6 Shortest distance to the landmark in the shape of ELLIPSE, including the particular case of landmarks in the shape of CIRCLE

```
Require: User position, in terms of (x, y) coordinates
    Landmark coordinate: the length of the major and minor axis (equal axis for the CIRCLE), centre
Ensure: The computation of the shortest distance to the landmark in the shape of ELLIPSE/CIRCLE
$M = minoraxis^2 - majoraxis^2$ {Findings the intersection with ellipse}
$N = minoraxis \cdot (center.x - position.x)$
$P = -majoraxis \cdot (center.y - position.y)$
Call the method solving the quartic equation 8.5 $-a^4 \cdot P + a^3 \cdot (-2 \cdot M + 2 \cdot N) + a \cdot (2 \cdot M + 2 \cdot N) + P = 0$ {Solution of this equation is tang(t/2)}
if The quartic equation has real solutions then
    if There are four real solutions then
        for $0 \leq k < 3$ {all real solutions} do
            $t[k] = 2 \cdot \arctan(root[k])$
            $x(t[k]) = majoraxis \cdot \cos(t[k]) + center.x$ {Coordinates of the four points of intersection with the ellipse}
            $y(t[k]) = minoraxis \cdot \sin(t[k]) + center.y$
            $Distance[k] = ((x(t[k] - position.x)^2 + (y(t[k] - position.y)^2))^{1/2}$
        end for
        $Distminellipse = Distance[0]$ {Initialisation}
        for $0 \leq k < 3$ {Finding the minimum distance among the four} do
            if $Distminellipse > Distance[k]$ then
                $Distminellipse = Distance[i]$
            end if
        end for
    end if
    if There are two real solutions then
        for $0 \leq k < 2$ do
            $t[k] = 2 \cdot \arctan(root[k])$
            $x(t[k]) = majoraxis \cdot \cos(t[k]) + center.x$
            $y(t[k]) = minoraxis \cdot \sin(t[k]) + center.y$
            $Distance[k] = ((x(t[k] - position.x)^2 + (y(t[k] - position.y)^2))^{1/2}$
        end for
        if $Distance[0] < Distance[1]$ then
            $Distminellipse = Distance[0]$
        else
            $Distminellipse = Distance[1]$
        end if
    end if
end if
Return Distminellipse
```

and 5.9. Several architectures have been tried (Sas et al., 2002, 2003b), in order to minimise the network prediction error. The network prediction has been computed as the sum of squared errors between target and obtained values (SSE), and the mean squared error (MSE) which is an aggregation of the error in the activation levels of the output neurons: MSE = SSE / (number of vectors − number of weights) (Zell et al., 1995). The architecture which led to the best performance has been retained. It consists of 7 input nodes, 7 hidden nodes, 7 context nodes and 7 output nodes (Figure 8.13).

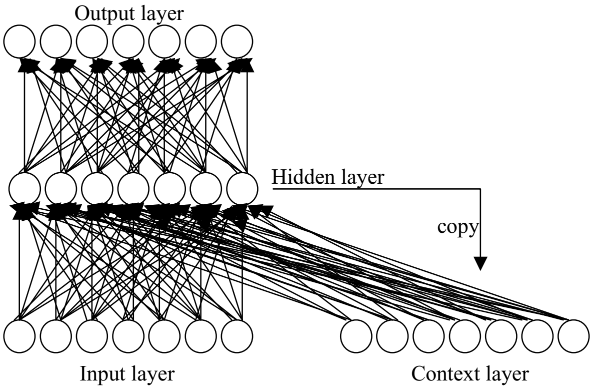


Figure 8.13: The Architecture of the Elman RNN Used for Trajectory Prediction

The network input consists of a sequence of users' trajectories. At each time step t, an input vector is presented consisting of user's position, orientation angle, distance to the nearest landmark, together with its associated position (coordinates of the centre of the landmark), and the floor where that movement took place. After each trajectory was entered, an input representing "reset" is presented, for which the network is supposed to zero out the outputs (Elman, 1990). The output pattern represents the input vector of time $t+1$. Using the backpropagation learning procedure (Elman, 1990), the network was taught to predict for each current position the next position in time.

The entire set of data was randomly divided into five parts, using two of them for training, one for validation and two for testing. The network was trained with 89 trajectories composed of 13062 input vectors. It was tested with 75 trajectories consisting of 11540 input vectors. The average trajectory length was 160 vectors. The learning rate was 0.001, the initial weights were within the range of (−0.5, 0.5), and the momentum was 0. The activation function was Tangent Hyperbolic, while the learning function was Jordan Elman BackPropagation. Table 8.1 presents an example of input/output vectors.

8.3.4 Network Performances

The network was trained for 100 epochs and the performances are summarised in Table 8.2. The imprecision of floating point arithmetic led to the presumption that a prediction is correct not only if it equals the expected value, but also if it is "close

Table 8.1: Input/Output Vectors Used for Training RNN for Trajectory Prediction — Excerpt

	User pos. X	User pos. Y	User Heading	Dist. to the nearest landmark	Landmark pos. X	Landmark pos. Y
input1	−0.000	0.109	0.999	0.031	0.000	0.078
output1	−0.000	0.109	0.999	0.031	0.000	0.078
input2	−0.000	0.109	0.999	0.031	0.000	0.078
output2	−0.000	0.156	0.999	0.078	0.000	0.078

Table 8.2: Summary of Performance Obtained by the RNN Used for Trajectory Prediction

	SSE	MSE	SSE/o-units
Train	1415.33	0.10836	202.191
Test	381.32	0.10845	54.475

enough" to it. This assumption has high face validity. Therefore in this thesis it is considered that the RNN produces an error if the Euclidean distance between the vector predicted by the network and the expected vector is above a given threshold. This threshold was set up for each element of the vector as follows: 1.5 virtual metre for the (x, y) coordinates of user's position and for the coordinates of landmark's position, 30 degrees for rotation angle, 1 virtual metre for the estimation of the distance to the nearest landmark and 0.3 virtual metre for the estimation of the z coordinate which is related to the prediction of the current floor of the virtual building. Table 8.3 presents the results of testing the network, obtained by computing the Euclidean distance between the output vector predicted by the network and the expected output vector.

Table 8.3: Summary of the Prediction Accuracy of Each Input Element Used for Training the RNN

Input description	Percent Correct
User's next position — X coordinate	98.79%
User's next position — Y coordinate	95.25%
User's next orientation (heading)	89.74%
Distance to next nearest landmark	97.07%
Next nearest landmark position — X coordinate	93.18%
Next nearest landmark position — Y coordinate	87.89%
Next level	94.71%

As can be seen, the network generalises well for all the input elements. However, for a prediction to be correct, all the input elements should simultaneously be within specified limits. A more conservative performance criterion was defined, which considers that an error occurs when at least one of the elements of the vector is above the threshold. With respect to the composite criterion of accuracy, the network still performs adequately, the success rate being 68.87% (Sas et al., 2002, 2003b).

The prediction performance obtained by the RNN supports the idea that the net successfully learned the regularities underlying the training data. Understanding what the network learned can be achieved by analysing the internal representation acquired by the network. Knowledge embedded into a trained RNN is stored in its weights and hidden nodes (Plunkett and Elman, 1997) (see Section 6.4.1). A straightforward way of evaluating RNN performance is through cluster analysis of the hidden node activation values (Morris et al., 2000).

8.3.5 Analysis of Hidden Layer

The hidden node activation values were recorded after each testing input vector has been presented to the network (Podolak, 1998). K-Means clustering analysis performed on these values revealed two clusters. A cluster membership was assigned to each vector and a series of statistical tests were performed in order to associate meaning to these clusters. Firstly the errors within each clusters are analysed.

Within cluster 1 there are significantly more correct predictions (56.7%) than in cluster 2 (43.3%), $\chi^2(1) = 32.44$, $p < 0.001$. If the number of prediction errors differs between the two clusters, it is conjectured that the clusters should be related to the user's performance. There are indeed significantly more input vectors belonging to efficient navigators or high spatial users, according to their performance on search task, in cluster 1 (58.2%) than in cluster 2 (41.8%), $\chi^2(1) = 29.85$, $p < 0.001$.

The percentage of prediction errors within each cluster was further analysed on the basis of the type of error associate with each element of input vector. The errors were considered as being related to one of the following events: translation, rotation and landmark prediction. No significant difference has been found with respect to the number of errors within each cluster, when errors were related to predictions of user's coordinates (x, y) or for the x coordinate of the centre of the landmark. The difference in number of errors was related to the prediction of the y coordinate of the centre of the landmark ($\chi^2(1) = 39.10$, $p < 0.001$) and of rotation angle ($\chi^2(1) = 11.24$, $p < 0.01$). Significantly more such kind of prediction errors had occurred within cluster 2.

Furthermore, the focus is on identifying what type of events characterise the clusters and whether there is any difference between them on this respect. Cluster 1 groups those hidden neurons that are significantly more respondent to the input vectors representing rotation and landmark prediction as opposed to translation prediction ($\chi^2(2) = 10.83$, $p < 0.01$).

The analysis of the internal representation acquired by the RNN performed through cluster analysis of hidden nodes has several limitations. It does not take into account the temporal dimension and it is not performed in the context of input and output vectors, of which the hidden nodes are intrinsically related. These limitations suggest that apart from clustering analysis one should employ other techniques to grasp the temporal dynamic and also to broaden the context of analysis.

One way to carry out such an investigation, which represents another contribution of this thesis, is through the use of time series analysis. A time series is a sequence of observations which are ordered in time (Warner, 1998). The elements within both input and output vectors represent time series, while the hidden node activation values represent time series as well.

8.3.6 Hidden Nodes Specialisation

The simplest analysis of the relationship between two time series is the lagged correlation, performed after removing any serial dependency within them (Warner, 1998). The cross-correlations coefficients have been computed at lag 30, between each element of the input vector and the hidden nodes activation values. The highest correlation and the associated lag was recorded. For each element of input vector the cross-correlation equal or higher than 0.70 has been retained and the associated hidden node was considered as specialised for that particular input element (firing for it). For each input element, the specialised hidden neurons are presented in Table 8.4. It is obvious that users' and landmarks' positions are mapped by similar hidden neurons, though the former requests more hidden nodes. The rotation angle requires a completely different set of hidden nodes.

Input element	H1	H2	H3	H4	H5	H6	H7
User's X coordinate		√		√			
User's Y coordinate	√				√		
User's rotation angle			√			√	√
Distance to the nearest landmark							
Landmark's X coordinate		√					
Landmark's Y coordinate	√						

Table 8.4: Specialisation of Hidden Nodes of RNN According to their Firing Patterns for the Input Elements

To conclude, the time series analysis consisting of lag correlation between input vectors and hidden node activation values revealed two groups of hidden neurons. These two groups of hidden nodes appear to be highly sensitive to the changes in input elements related to places and respectively to orientation. In other words, the analysis of the representations in the hidden layer suggested that the distinct groups of hidden units become specialised for place and direction (O'Keefe and Nadel, 1978) (see Section 3.2.3).

8.3.7 Spatial Representation

Psychological studies have been carried out in order to provide a better understanding of how humans perceive and understand the space (Piaget and Inhelder, 1967). The work described here confirms the idea that acquiring an internal representation of the environment is a complex process involving primarily landmark identification and the understanding of spatial layout. These two basic procedures are well known as route-based knowledge and survey knowledge (see Sections 3.2.2 and 3.2.3).

The connectionist simulation described in Section 8.3.3 was also used to test whether a RNN can build a cognitive map as an internal representation of environmental information (Golledge, 1999). Such a representation has been tested in terms of landmarks and configuration of the spatial layout.

At this stage, the notion of landmark has been expanded to any feature added to spatial layout. Therefore, apart from any piece of furniture, the choice points such as doors and lift entrance were also considered landmarks. Identifying which ones among these features prove to be salient and able to capture attention — being thus an authentic landmark — is a task to be solved by the network.

Figure 8.14 presents the "cognitive map" derived from network representation of landmark positions. It shows the layout of the virtual space (ground floor) in terms of the centres of the landmarks: (x, y) coordinates, as the RNN predicted them. As it is shown, the predicted coordinates of the landmarks form clusters around the coordinates of the landmarks within the VE. The centroids for each cluster are plotted as well.

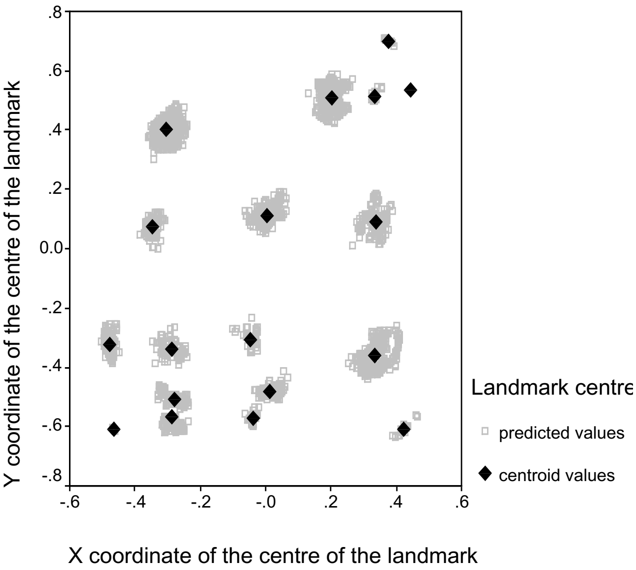


Figure 8.14: Centres of the Landmarks Predicted by the RNN

For understanding the accuracy of predicting the landmarks, Figure 8.15 presents the actual centres of the landmarks together with the centroids of the centres' of landmarks, as predicted by the RNN.

As can be seen from Figure 8.14 and 8.15, the "cognitive map" (the internal representation of space acquired by the RNN) conserves both the topology and the metric. While the topology has been remarkably learned, the metric is less accurate. The same

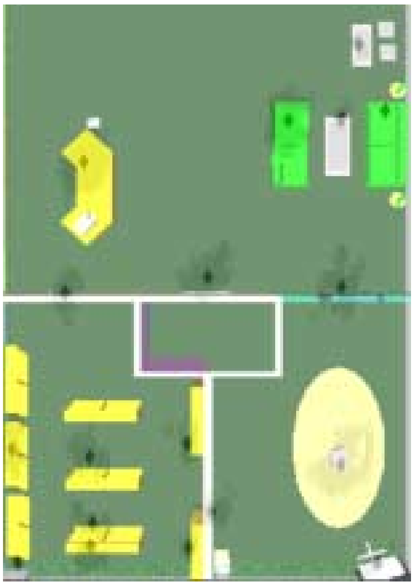


Figure 8.15: Original Landmarks Centres and the Centroids of their RNN Prediction

properties characterise the cognitive maps built by humans (see Section 3.2.2). For a better understanding of the network's ability to discriminate between landmark features, an analysis of network predictions, regarding the attention it paid to each landmark, has been performed. More precisely, it has been counted how many times a landmark was visited, or in other words how many times a given landmark was the nearest to the user. This measurement has been considered an indicator of landmark saliency. Findings suggest that the saliency of a landmark is related to the landmark's location in the room, such as centrality, its size, and uniqueness (i.e. shelves in the library are all alike, thus undistinguishable). Users paid particular attention to connectivity/decision points such as doors and lift which also represent salient landmarks.

8.3.8 Conclusions

The results have been obtained through a neural network simulation of human spatial behaviour performed within a VE. The main purpose of the simulation consisted of movement prediction, performed with the goal of extending our understanding of such behaviour. The preliminary findings are promising, indicating that the network successfully learned to predict the user's next location and heading, together with the nearest landmark (prediction accuracy above 68%).

The cluster analysis of hidden node activation values highlighted two groups of vectors which present several significant differences. Cluster 1 is that for which the prediction is significantly better, and therefore, unsurprisingly, is associated with input vectors belonging to high spatial users. The higher number of errors in prediction appearing in Cluster 2 is mainly due to the inaccurate prediction of the rotation angle. The main conclusion is that RNN encounters difficulties in learning the rotation behaviour of low spatial users. Future work should be carried out in order to understand which aspects differentiate rotations performed by efficient navigators, aspects whose regularity seems to be better understood by the network (see Chapters 9 and 11).

This simulation has not been concerned with the biological plausibility of human spatial behaviour (see Section 3.2.3). However, a closer analysis of hidden layer suggests a specialisation of hidden neurons, specialisation that resembles the neurons' organisation within the hippocampus (O'Keefe and Nadel, 1978; Redish, 1997). The two groups of neurons whose firing patterns correlate dynamically with the elements of the input vector, could be associated with the place and heading cells respectively. This is an outcome which confirms the validity of the employed time series analysis.

Findings also suggest that some abstract aspects related to spatial cognition are learnable. The basic idea is that by mapping an input vector consisting of current Cartesian coordinates together with information about the nearest landmark are sufficient to induce the internal abstractions to predict the next position. Moreover, the network is able to understand the spatial configuration of the VE.

The network was also able to learn the boundaries of the spatial layout, and even to build a cognitive-like map. At the same time, it did not over-generalise (Morris et al., 2000). The spatial representation of the virtual world preserves the topology, while the metric is less accurate. The network was able to assign saliency to landmarks, related to their location (e.g. centrality in the room frame, their size, distinctiveness etc.).

8.4 Rule Extraction

The human ability to succeed in navigational tasks of any kind depends on how humans understand the space in which they are navigating. This involves an implicitly developed representation of the spatial layout, usually in the shape of so-called cognitive maps (see Section 3.2.2). Despite its significance, the process of building such representations raises difficulties. The classical methods for studying cognitive models such as interviews, protocol analysis or map drawing present limitations related primarily to the implicit content of the information which the researchers try to elicit (see Section 3.2.4). Therefore, this thesis advocates employing ANNs as a suitable tool for rule extraction.

The RNN successfully learned to predict user's next position and orientation. The prediction accuracy of greater than 68% suggested that the neural network succeeded in acquiring the underlying regularities characterising user trajectory patterns (Section 8.3.3).

The next step consisted of extracting rules that characterise human heuristics for exploring an unfamiliar, indoor environment. This section proposes a hybrid connectionist-symbolic model for investigating rules governing human exploratory behaviour within VEs. Its final aim is to extract a spatial grammar underlying spatial knowledge acquisition. Such a spatial grammar is an inherent part of user mental model of navigation, which will be harnessed for designing adaptive VEs able to support low spatial users to improve their spatial behaviour (see Sections 11.4.3 and 11.4.5).

The analysis of the representation in the RNN hidden layer suggested that distinct groups of hidden units become specialised for place and direction (Section 8.3.5). The distributed representations acquired by RNN should be also investigated by analysing the individual pattern error in the network prediction (see Section 6.4.1).

8.4.1 Pattern Error Analysis

Before starting to analyse the pattern error for each of the RNN's predictions, a decision should be made regarding the sample of these predictions which are worth being thoroughly investigated. It is clear that not all the predictions could act as indicators of the regularities embedded in the movement paths, but only the best predictions can qualify for this. Thus, a conservative criterion of selection has been chosen, which has been met only by the best predictions, such as the top 10% of them.

The best predictions have been identified on the basis of the following performance criterion, which requires that the threshold values should be set up rather low. For a particular input vector: (ix, iy, irot, idist, ixlandmark, iylandmark, ilevel), the predicted user's position or landmark position coordinates could differ only by ±0.5 virtual metre from the input position coordinates, the predicted user's heading should be higher or smaller with no more than 15 degrees from the input heading, the predicted distance to the nearest landmark could differ only with ±1 virtual metre from the input distance and the predicted floor value should not differ with more than ±0.3 virtual metre from the input floor value.

8.4.2 Clustering Neural Network Predictions

The analysis of the individual pattern error in the network prediction could prove beneficial in understanding the internal representation acquired by the network (Plunkett and Elman, 1997). The RNN is able to predict accurately specific patterns, only when it previously acquired the regularities underlying those patterns. The rule extraction process aimed to reveal the regularities which allow the RNN to make highly accurate predictions of user's position, heading, nearest landmark and floor.

I conjecture that understanding how and why the RNN succeeded or failed to predict accurately particular patterns could offer an understanding of navigation procedures or strategies employed by the participants in this study.

Given the specifics of these data and the objective of this thesis, a data mining technique has been employed. Self-Organising Maps (SOM) have been already introduced in Section 6.3.1. SOM is based on an unsupervised learning process, allowing cluster identification and visualisation within the input data. This process is carried out without any prior knowledge regarding the number and content of the clusters to be obtained (Kaski, 1997). When a set of already clustered input data is available, a supervised learning process, such as Learning Vector Quantisation (Kohonen et al., 1995) can be employed to identify to which class an unknown data vector belongs (see Section 6.4.4).

The use of SOM (Kohonen et al., 1996) and LVQ (Kohonen et al., 1995) for performing the cluster analysis of RNN error prediction requires several steps, as described in Section 8.2. These generic steps have been adapted for the current analysis and the modules which serve each of these steps are presented in Figure 8.16.

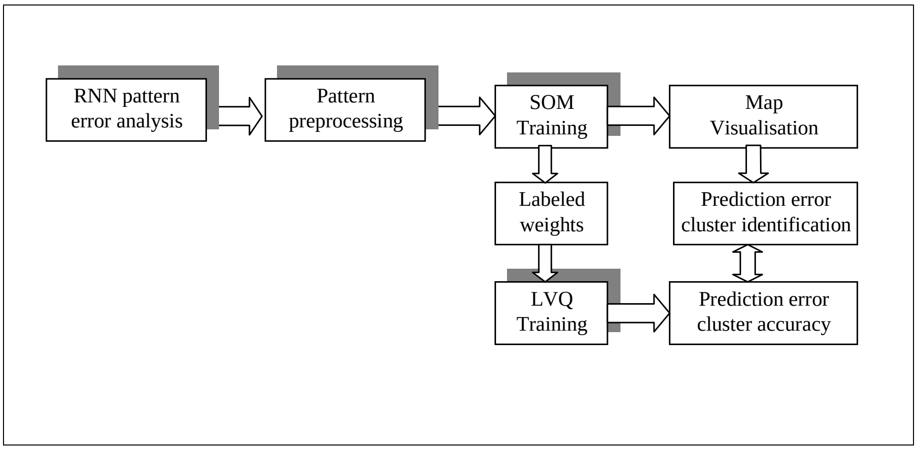


Figure 8.16: Modular System for Clustering the RNN Prediction Error

8.4.3 Pre-Processing Data

Navigation is a spatio-temporal event, where the position of each moment t depends on the position of moments $t-1$, $t-2$,. . . , $t-n$, and in the same time, influences the position at subsequent times: $t+1$, $t+2$,. . . ,$t+n$. Thus, one should consider not only the pattern which has been successfully predicted, but also the history in terms of previous patterns which had led to that highly accurate prediction. In other words, the attention is paid to the interesting pattern, considered in its context. Therefore, once a particular pattern has been identified as described above, the context in terms of its previous nine patterns has been also recorded.

For each of these patterns, the predicted values for user's position and heading have been retained and concatenated with the corresponding values from the previous patterns. The values have been normalised between -1 and 1. The obtained vector consisted of 30 input elements, three for each of the ten moments in time, and looks like it follows:

$$(px[9], py[9], prot[9], px[8], py[8], prot[8], \ldots, px[0], py[0], prot[0]) \tag{8.6}$$

8.4.4 Training SOM

The training set and the testing set have been identified by analysing the prediction errors associated with the counterpart sets used for training and testing the RNN. The training set consisted of 1367 vectors (54%), while the testing set consisted of 1167 vectors (46%). Each of these two sets covered the top 10% best predictions produced by the RNN, during training and testing respectively.

A SOM of 20×16 neurons was used to perform a topology-preserving mapping. The first phase of training was carried out for 1700 epochs, a radius of 20 and a learning rate of 0.3, while the second phase lasts for 21 000 epochs, with a learning rate of 0.07 and a radius of 2. The random seed of 115 was identified by using the *vfind program.* These parameters were retained, after more than 100 networks with different architectures and learning rates have been tried, because these particular parameters led to the smallest quantisation error (Kohonen et al., 1996) for the testing set: 0.36, while for training set it was 0.31.

8.4.5 Map Visualisation

Training the SOM led to seven clusters of RNN best predictions, as shown in Figure 8.17. For their identification, within the area corresponding to each of them, the assigned cluster number has been placed. For example, cluster number 1 consists of segments of trajectories standing for best predictions, within area designated by number 1, located down on the right hand side of the map.

8.4.6 Cluster Identification

The winner nodes within each cluster are represented as plots on the Cartesian coordinates system (X,Y), on a zoomed-in area of the SOM map. For a better understanding, both user's position and heading have been plotted (Figures 8.18, 8.19, 8.20, 8.21, 8.22, 8.23 and 8.24), for each of the 10 moments in time (i.e. one when the best prediction has been identified, and the previous nine). The lightest colour is used to represent the further position and heading in time, while the darkest one marks the present moment when the best prediction has been identified. The different shades of grey on the light–dark continuum offer an intuitive understanding of the temporal dimension embedded in these data, from past to present.

8.4.7 Training LVQ

In order to test the accuracy of classification provided by SOM, the LVQ algorithm has been used. The training and testing sets for LVQ have been derived from the SOM training and testing set respectively, while the cluster labels have been attached to each input element as the SOM map suggested. In addition, once the SOM was trained, the codebook vectors have been used for initialising the weights for the LVQ algorithm.

The obtained classification accuracy was 95.15%. Within each cluster, the classification accuracy varies as follows: cluster 1 — 92.65%, cluster 2 — 100%, cluster 3 — 98.48%, cluster 4 — 94.72%, cluster 5 — 93.44%, cluster 6 — 95.28%, and cluster 7 — 91.49%. As can be seen, the accuracy for the all the clusters is high. This outcome suggests the validity of the clusters previously identified. Once the clusters have been identified, the following step consists of their interpretation.

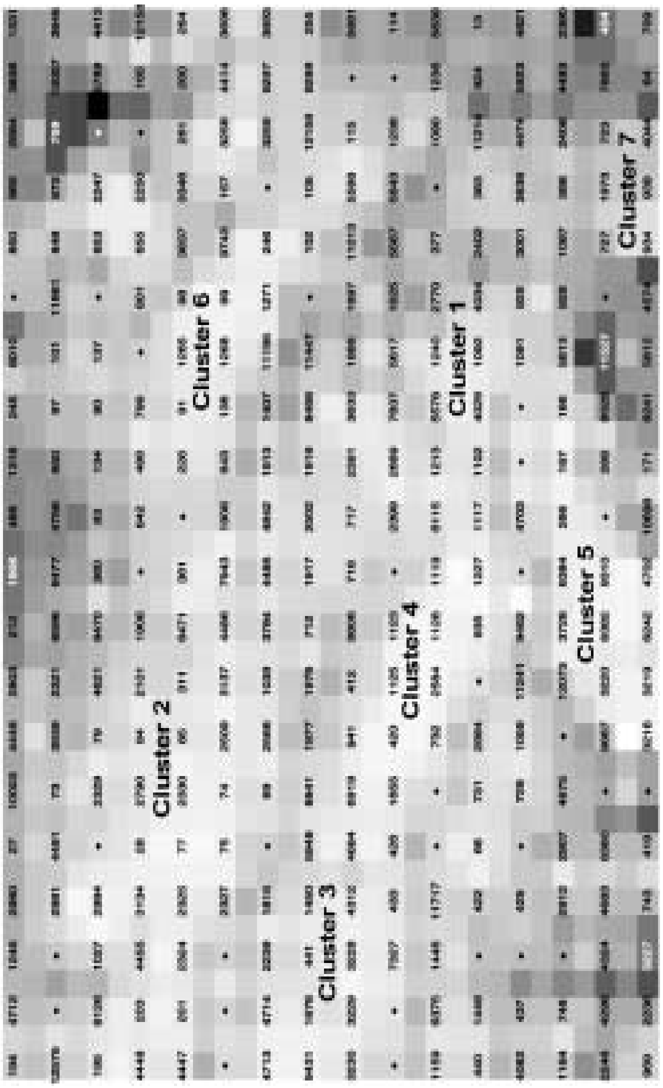


Figure 8.17: SOM of the Best Predictions of RNN Used for Trajectory Prediction

8.5 Symbolic Rule Induction

In order to understand the meaning associated with each cluster, the rule induction algorithm C5.0, based on ID3 algorithm (see Section 6.4.3) has been used. The C5.0 method is based on the ID3 (Quinlan, 1993) algorithms which induce concepts by examples. It is particularly interesting due to its representation of learned knowledge, its approach to the management of complexity and its heuristic for selecting candidate concepts. It represents concepts as decision trees, a representation that facilitates the classification of an object by testing its value for certain properties (see Section 6.4.3). The advantage of employing such an algorithm, particularly in combination with ANNs, has been suggested by Dubitzky et al. (2001):

> Decision trees belong to the class of so-called symbolic methods. The attractiveness of decision trees is largely due to their ability to express the learned models as symbolic rules that can readily be understood by humans. Neural

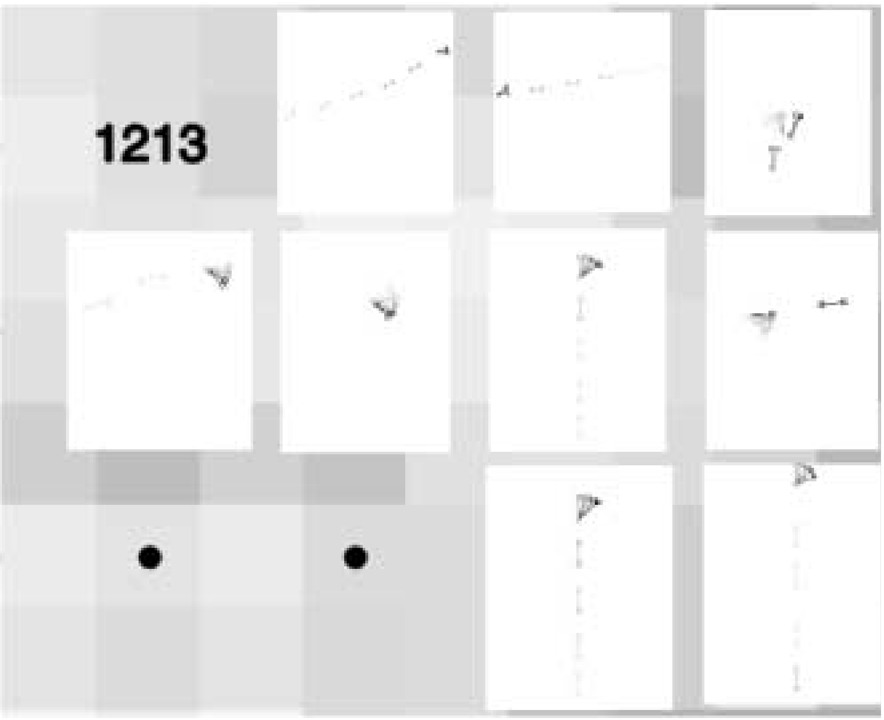


Figure 8.18: SOM – Cluster 1

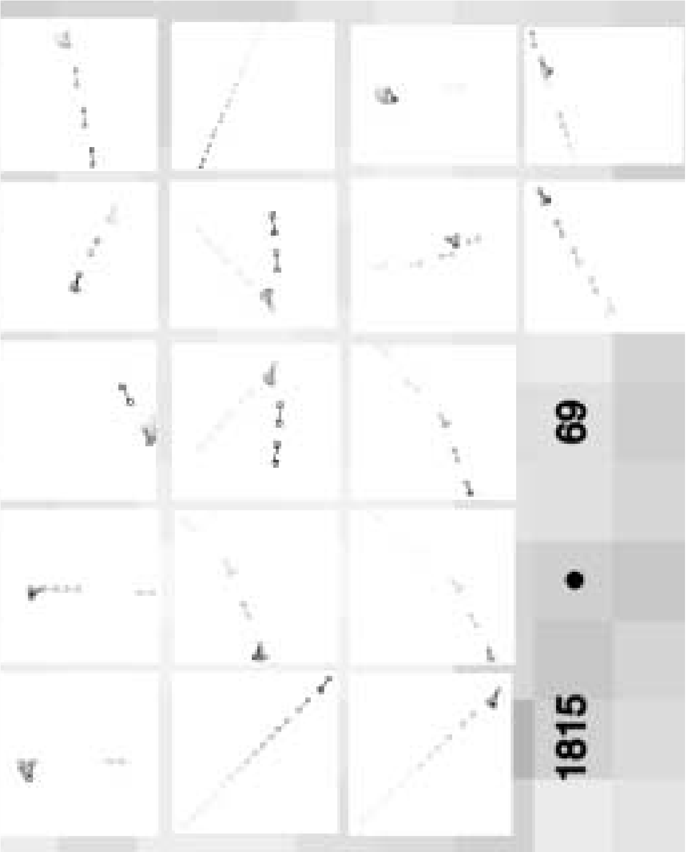


Figure 8.19: SOM – Cluster 2

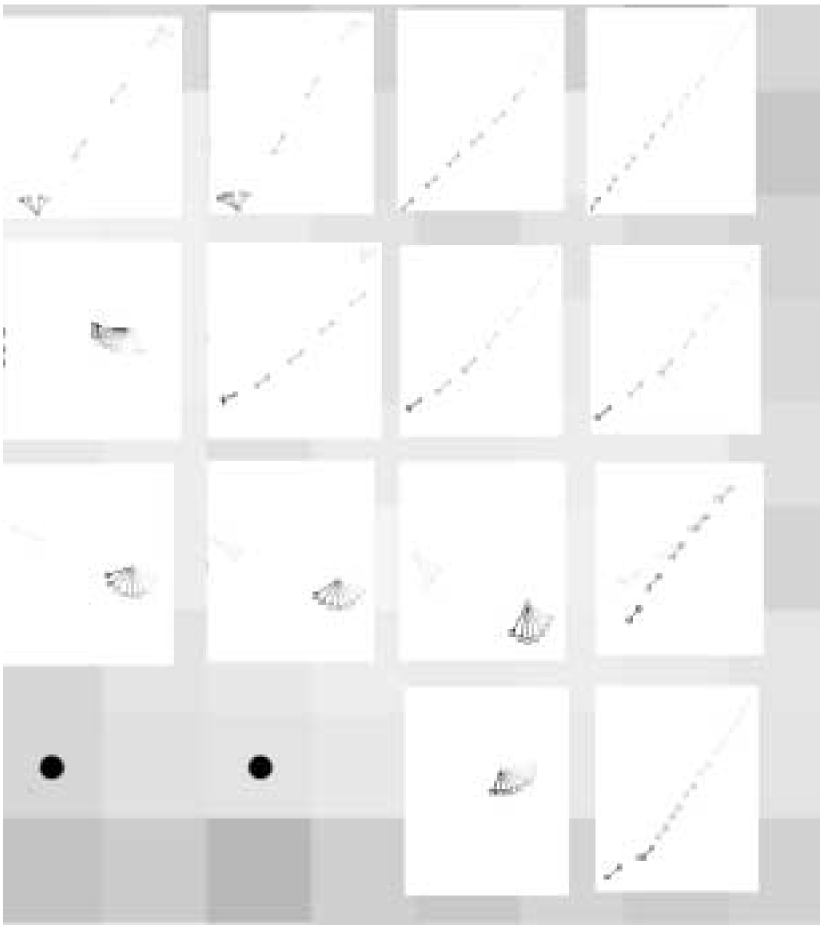


Figure 8.20: SOM – Cluster 3

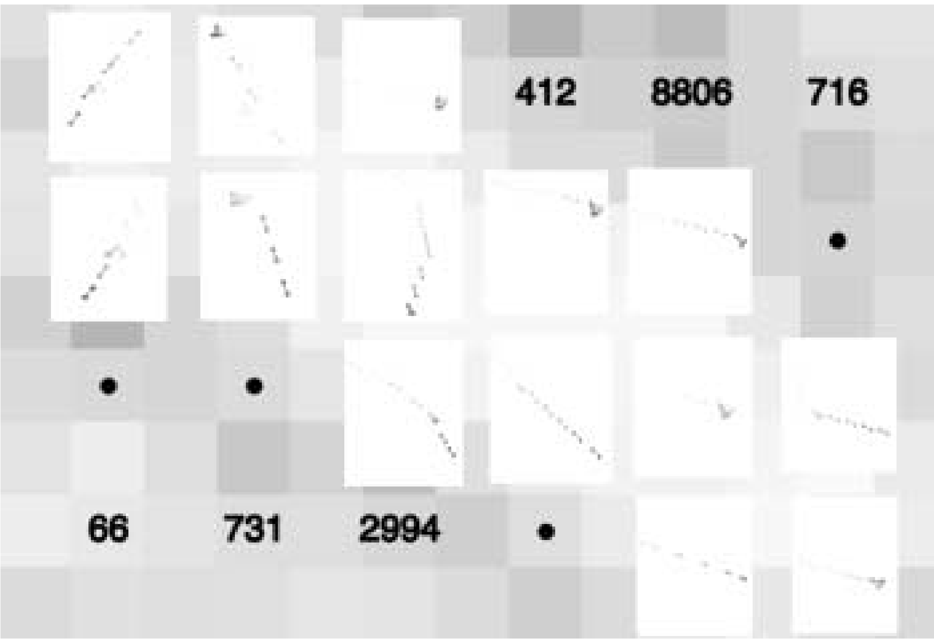


Figure 8.21: SOM – Cluster 4

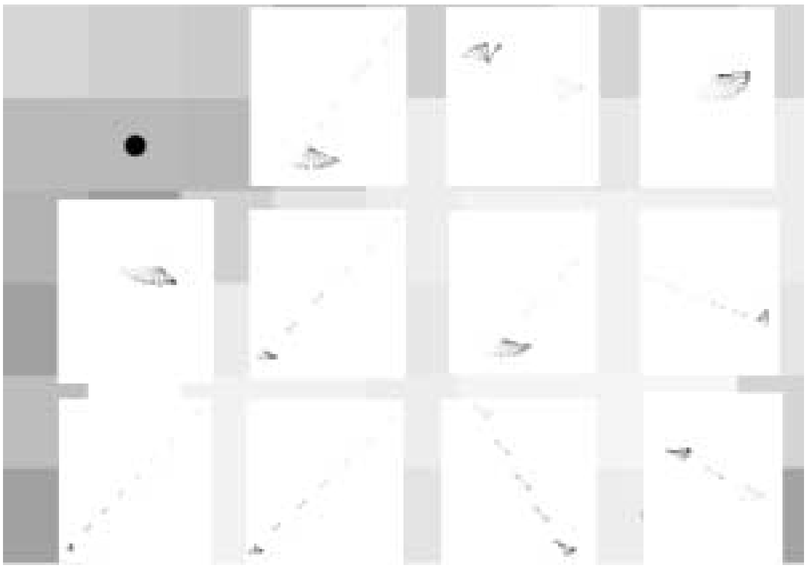


Figure 8.22: SOM – Cluster 5

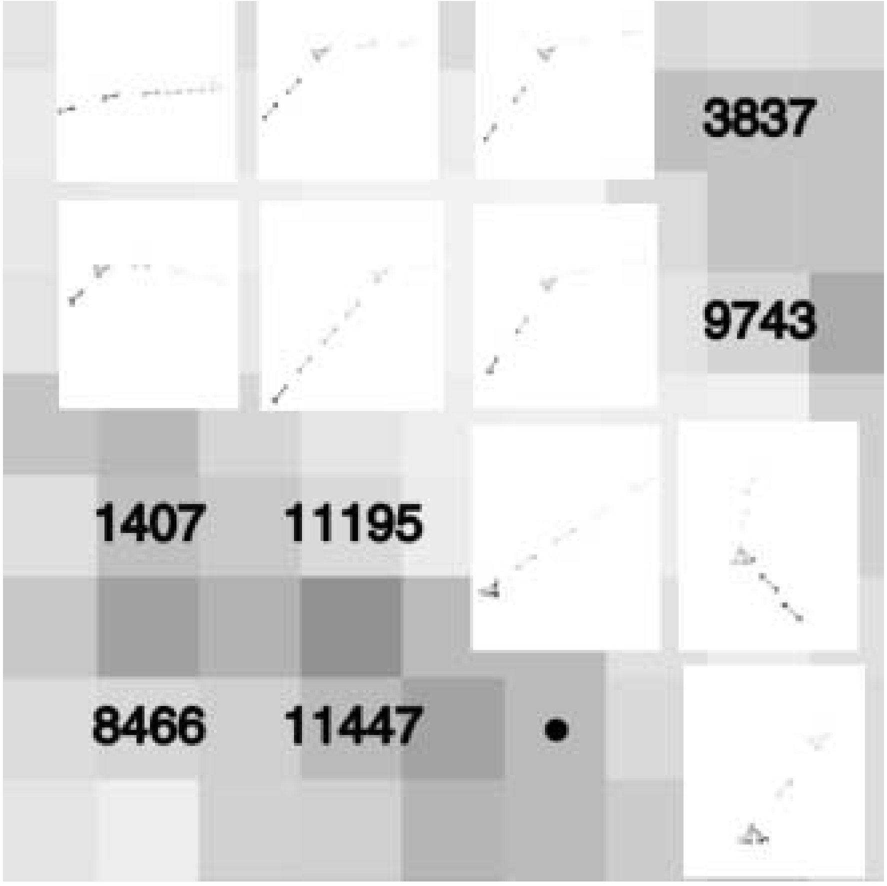


Figure 8.23: SOM – Cluster 6

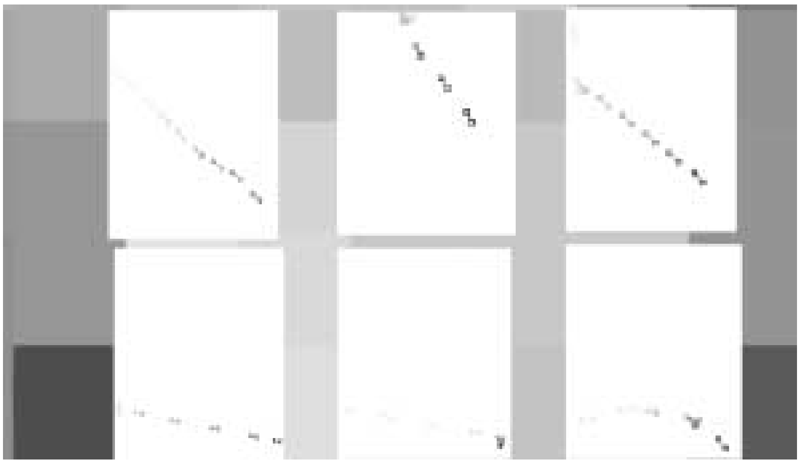


Figure 8.24: SOM – Cluster 7

> network approaches, on the other hand, represent their learned knowledge as patterns of connectivity that exist among the nodes of the network. This type of knowledge representation is sometimes called subsymbolic, and is not readily intelligible by humans.

The stages involved in Symbolic Rule Induction are depicted in Figure 8.5.

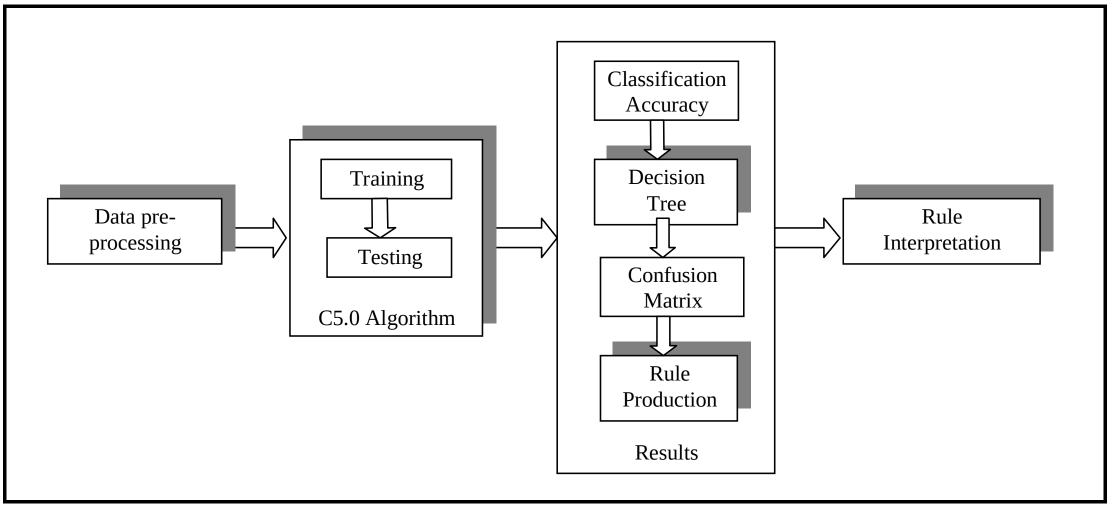


Figure 8.25: Modular System for Symbolic Rule Induction

8.5.1 Pre-Processing Data

Pre-processing data for the Quinlan (1993) algorithm involves some transformations in order to reduce the data redundancy and complexity, while preserving its essential features. For an easier interpretation of the results, the data has not been normalised. The exact (x,y) coordinates of users' and landmarks' positions expressed in virtual metres offer an unnecessarily high level of accuracy. Therefore, a grid of 16×27 locations has been overlapped on the spatial layout, enabling a reduction of dimensionality, from two dimensions to one dimension. This grid provides a location for each square of 1×1 virtual metre of the virtual space. In addition, the heading has been also simplified by approximating it with one of the eight major directions: 0°, 180°, ±45°, ±90°, ±135°. The classifiers are the cluster numbers previously identified by training the SOM.

8.5.2 C5.0 Algorithm

The training and testing file contained 471 and 348 vectors respectively, encoding user's location, landmark's location and user's heading, from the moment when the best prediction has been identified (t_9) until the farthest in time (t_0). The training had been performed using the boosting option which ensures the production of several decision trees or rule sets whose votes are counted in order to determine the final class for a new case (Quinlan, 1993).

8.5.3 Classification Accuracy

The result of 10-fold boosting was 94.5% indicating a high accuracy of the classification over the test set, while the non-boosting version of the decision tree achieved an average classification accuracy of 83.5%.

8.5.4 Decision Tree

The decision tree generator, part of the C5.0 package, takes as input the training set of 30-dimensional vectors, described on the bases of their values for the attributes like user's and landmark's location and user's heading at ten moments in time: the one where the accurate prediction has been identified and the previous nine. It produces as output the decision tree presented in Table 8.5. Each leaf of the decision tree is assigned to a class with certain accuracy. For instance, the last leaf belongs to class 4 (76.2/16.2), for which n = 76.2 represents the number of cases in the training set, that are mapped to this leaf, while m = 16.2, represents the number of cases that are misclassified by this leaf.

8.5.5 Confusion Matrix

The Table 8.6 presents a confusion matrix for the general decision tree resulting from the C5.0 induction rules. The rows represent the actual classification for the data, while the columns represent the prediction of the class from the C5.0 rule. For example, it is shown that a case identified as cluster 2 is 100% accurate as all cases that belong to this type of class are predicted correctly. On the other hand, if a case is predicted as belonging to class 7, there is only 68% accuracy, since it can be also associated to class 1 or class 4.

Table 8.5: Decision Tree Generated by the C5.0 Rule Induction Algorithm

- loc9 $>$ 291:
  - loc4 $>$ 365:
    - rot9 $\leq$ -45: **3** (14.9)
    - rot9 $>$ -45: **5** (38.1/1.6)
  - loc4 $\leq$ 365:
    - rot9 $>$ 0: **5** (16.7)
    - rot9 $\leq$ 0:
      - locc9 $\leq$ 254: **4** (3.2)
      - locc9 $>$ 254: **3** (45.6)
- loc9 $\leq$ 291:
  - rot8 $\leq$ -45:
    - loc9 $>$ 249: **4** (17.3/7.6)
    - loc9 $\leq$ 249:
      - locc9 $>$ 227: **2** (40.2)
      - locc9 $\leq$ 227:
        - locc9 $\leq$ 184: **2** (20.1)
        - locc9 $>$ 184: **6** (31.7)
  - rot8 $>$ -45:
    - locc7 $>$ 265: **1** (13)
    - locc7 $\leq$ 265:
      - locc9 $\leq$ 233:
        - locc6 $\leq$ 131: **7** (15.2/6.8)
        - locc6 $>$ 131:
          - loc9 $>$ 237: **6** (19.3)
          - loc9 $\leq$ 237:
            - rot8 $\leq$ 0: **6** (5.1/1.7)
            - rot8 $>$ 0: **1** (26.6)
      - locc9 $>$ 233:
        - loc9 $>$ 243: **4** (62.7/9.9)
        - loc9 $\leq$ 243:
          - loc9 $\leq$ 212: **7** (7.6)
          - loc9 $>$ 212:
            - locc8 $>$ 243: **7** (2.7)
            - locc8 $\leq$ 243
              - locc5 $\leq$ 174: **7** (14.8/4.7)
              - locc5 $>$ 174: **4** (76.2/16.2)

Table 8.6: Confusion Matrix Generated by the C5.0 Rule Induction Algorithm

	class 1	class 2	class 3	class 4	class 5	class 6	class 7
class 1	87						13
class 2		100					
class 3			100				
class 4		2		93			5
class 5			6		94		
class 6		1		5		94	
class 7	9			23			68

8.5.6 Rule Production

The production rule generator constructs from the original decision tree a set of rules, expressed in the form of IF–THEN, which are more comprehensible than the decision trees. Each rule consists of:

- A rule number which identifies the rule.
- Statistics (n, lift x) or (n/m, lift x) that summarize the performance of the rule, where:
  - n is the number of training cases covered by the rule,
  - m is the number of training cases misclassified by the rule,
  - $(n - m + 1)/$(n+2) is the rule's accuracy,
  - lift is the rule's accuracy divided by the relative frequency of the predicted class in the training set.
- Condition(s),
- Class predicted, and
- Confidence with which the prediction has been made.

For example, one of the rules which predict class 2 is presented below (Table 8.7). Rule 3 means that if the rotation performed at the moment t_9 (when the best prediction has been identified), is less than 45 degrees and user's location at the previous moment t_8 is less or equal to 248 and the landmark's location at moment t_7 is greater than location 227, than the class 2 is predicted with 0.972 confidence.

8.5.7 Rule Interpretation

Cluster Specialisation The quality of the rules, such as good or poor, determined accordingly to the percent of trajectories performed by efficient navigators vs. inefficient navigators within each cluster carries an important role in the following descriptions.

There is a significant difference ($\chi^2(6) = 36.96$, $p < 0.01$) regarding the number of best predictions for trajectories performed by high spatial users, comparing with the

Table 8.7: Rules Generated by the C5.0 Rule Induction Algorithm — Excerpt

Rule 9/3: $53.2/0.6, lift 6.3$
rot9 ≤ 45
loc8 ≤ 248
locc7 > 227
$\rightarrow$ class 2 [0.972]

ones performed by low spatial users, within the previously identified clusters. However, chi-square is an overall test which indicates significant differences if there are significant differences between at least two cell frequencies. In order to identify exactly which pairs of cells differ significantly within the contingency table 2×7 (2 groups of users and 7 clusters), post-hoc tests were performed. Significant differences between the number of predictions associated with efficient and inefficient user movement patterns have been identified within Cluster 2 ($\chi^2(1) = 36.97$, $p < 0.0001$), Cluster 3 ($\chi^2(1) = 19.91$, $p < 0.0001$), Cluster 4 ($\chi^2(1) = 5.55$, $p < 0.01$), and Cluster 6 ($\chi^2(1) = 25.59$, $p < 0.0001$). No specialisation has been identified for Cluster 1, 5 and 7.

These results suggest that Clusters 2 and 3 reflect good rules or good navigational strategies, while Cluster 4 and 6 represent bad rules. In the following sections, symbolic rules will be associated with these clusters, and their interpretation will be described in detail. For a better understanding, overhead images or maps of different levels of the virtual building, which are directly related with each cluster, are provided.

Cluster 1 does not show any specialisation, suggesting that the rule which it represents has been equally employed by both efficient and inefficient navigators. This is because it consists of a basic spatial behaviour which is worth mentioning. This cluster groups the best predictions which occurred on the ground floor and the first level, within the area enclosed by the black rectangle drawn in Figures 8.26 and 8.27.

Cluster 1 groups the segments of trajectories performed in the very initial stage of exploring or revisiting a level. The user locations are usually within the perimeter of the virtual elevator or just in front of it. The movements consist of a set of translations from the starting point, usually in the direction of the initial heading (e.g. North), ending always with rotations involving considerable changes of heading.

In other words, this cluster suggests the following rule: from an initial position, move 1–2 metres in the direction of the heading and then perform rotations, to acquire knowledge of the spatial layout and in particular about the nearest landmarks.

Cluster 2 groups the best predictions which occurred on the ground and second floor, within the area enclosed by the black rectangle drawn in Figures 8.28 and 8.29. This cluster has been identified as representing a good rule and offers a generalisation of the rule associated with Cluster 1. Similar to Cluster 1, Cluster 2 encompasses movement

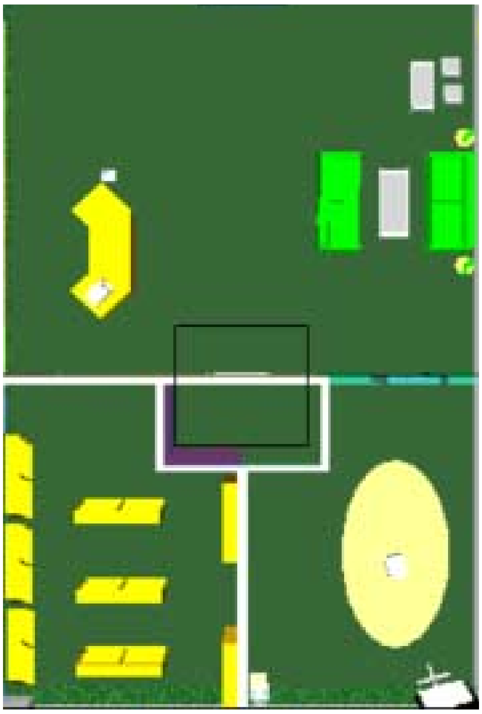


Figure 8.26: Cluster 1, Level 0

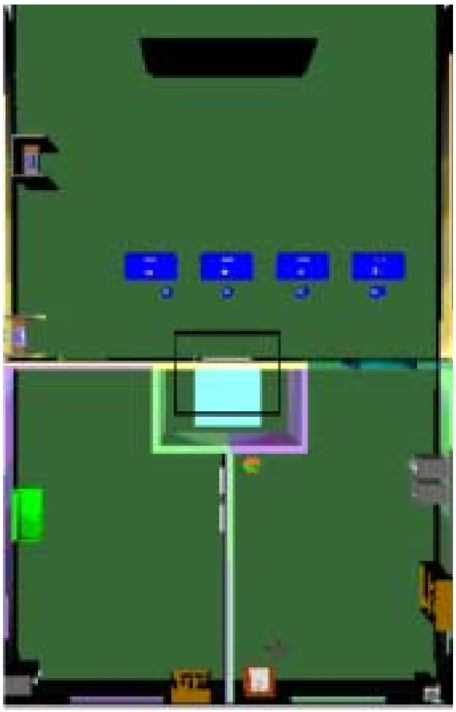


Figure 8.27: Cluster 1, Level 1

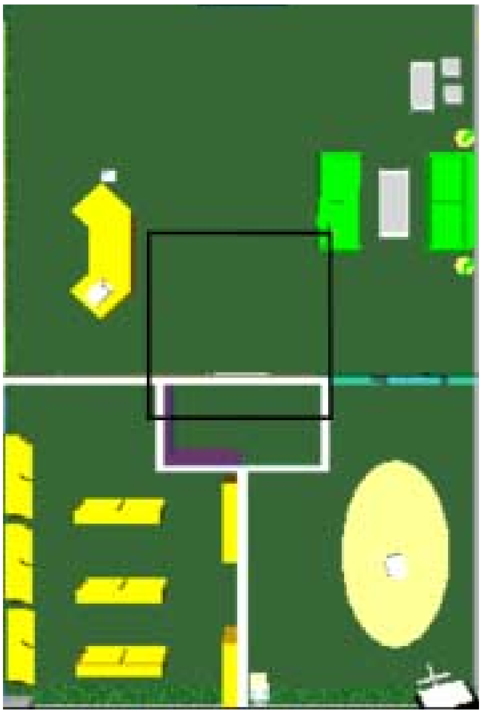


Figure 8.28: Cluster 2, Level 0

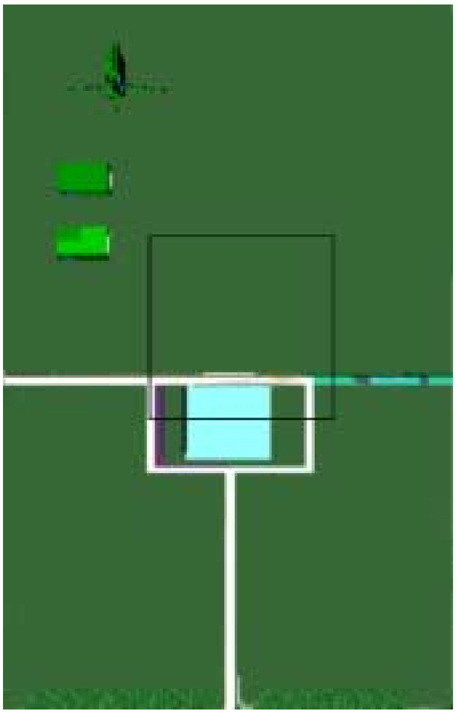


Figure 8.29: Cluster 2, Level 2

patterns close to the starting point, but an additional feature can be identified. The translations are performed in the major open area located closer to the starting point, area which can expend until some remarkable landmarks can be identified (e.g. almost until the middle of the bigger room). The segments of trajectories which have been grouped by this cluster belong to the ground floor or level 2, but not to the level 1 or 3, which do not offer an open area for such an exploration.

Some of the user's actions consist of translations towards the North direction which are followed by rotations. Such changes of heading allow the users to acquire a better view field. This behaviour is an extension of the one suggested by cluster 1. The difference is that these rotations are performed on a location closer to the centre of the bigger room. Actually the centre of this larger open area acts as a *virtual* landmark whose attractiveness, based on its location, resides in the largest overview that the user is enabled to acquire.

Cluster 3 groups the best predictions which occurred on the first, second and third floor, within the area enclosed by the black rectangle drawn in Figures 8.30, 8.31 and 8.32. This cluster groups segments of trajectories performed by the users with high performance in the search task, performance which could be reached only on the basis of good navigational strategies.

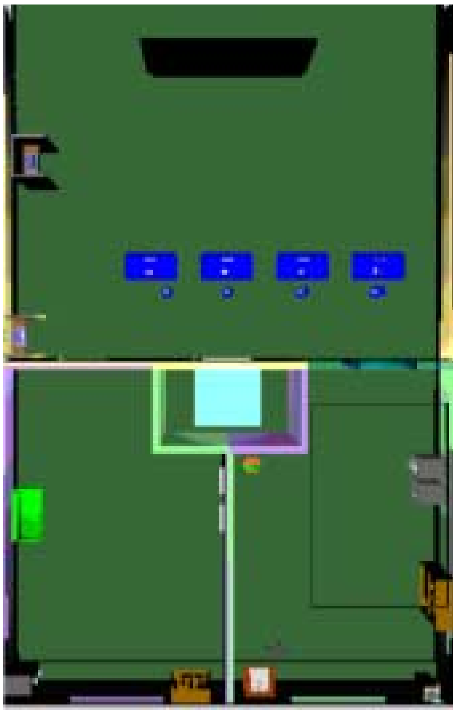


Figure 8.30: Cluster 3, Level 1

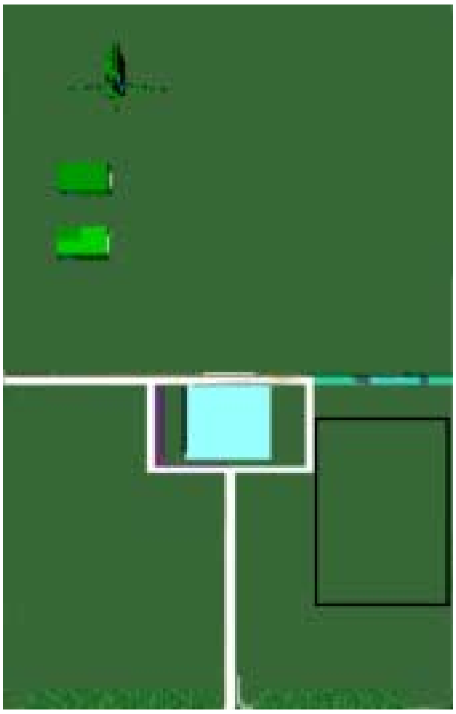


Figure 8.31: Cluster 3, Level 2

Cluster 3 groups the best predictions related to the exploration of the middle area of the small room, located on the right hand side of the spatial layout. The levels associated with this cluster are all but the ground floor, which is populated with several

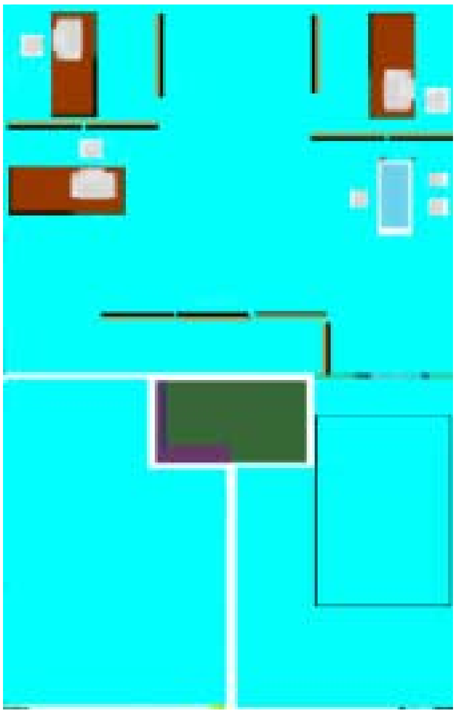


Figure 8.32: Cluster 3, Level 3

landmarks in the area targeted by this cluster. This aspect impedes users to carry out a good coverage of it.

Within Cluster 3 the users' movements, usually heading towards South-West, are translations performed from the upper part of the room towards the middle of it, or from the middle towards the lower part. Interestingly, this movement patterns resemble only vaguely the wall following behaviour, typical for exploration (Section 2.3.2). It seems, that the currently employed strategy allows users to cover the space more efficiently, according to the energy conservation principle (Maupertius, 1750), as compared to the wall following technique.

Actually, the users seem to navigate somewhere on the median space between the nearby landmarks or between the nearby landmarks and the room walls. This trajectory course keeps open several options, since the user can move towards any of these landmarks, with minimum energy consumption. Such movement patterns require only small translations but considerable changes of heading.

Cluster 4 groups the best predictions which occurred on the ground, first and third floor, within the area enclosed by the black rectangle drawn in Figures 8.33, 8.34 and 8.35. This cluster has been identified as representing a poor rule.

Cluster 4 groups the segments of trajectory encompassing two referential landmarks: the entrance to/exit from the virtual elevator and the door between the big room and the small room from the right hand side of the spatial layout. The actions within this cluster represent entrances from the big room to the adjacent smaller room. The area

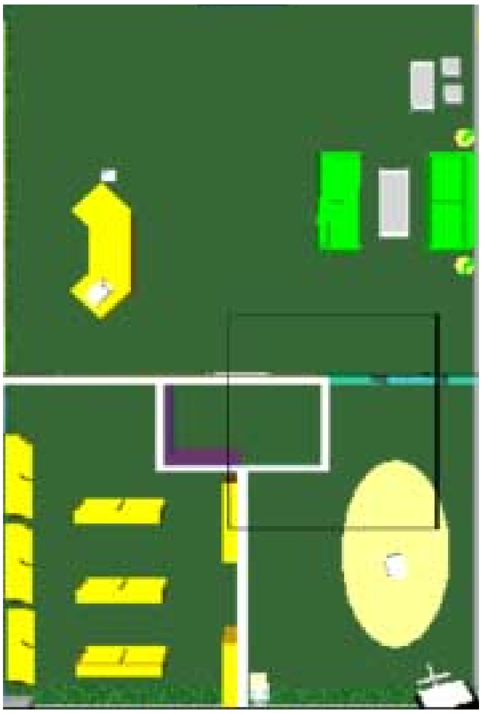


Figure 8.33: Cluster 4, Level 0

Figure 8.34: Cluster 4, Level 1

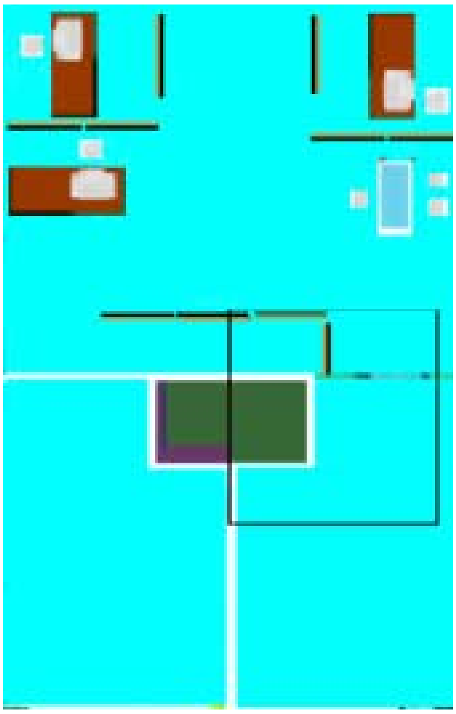


Figure 8.35: Cluster 4, Level 3

from which these movements are originated is approximately 3 metres further from the separating wall between these two rooms.

Each door in the virtual building is a sliding door, which means that it opens when the user is in its proximity, such as 1–2 metres, and closes when the user is further away. In addition, the intention to pass through the door as opposed to passing by the door, should be indicated by the heading. The closest the user's heading is to the orthogonal direction on the door, the higher the probability that the door will open. The door remains close when one's heading is parallel with the door, even when one's location is very close to the door. Moreover, going through the narrow passage of the door, within a limited time frame, involves additional cognitive overload which impedes the performance of low spatial users. This kind of door requires skilled users whose eye-hand coordination works well, who can estimate both the distance and the heading needed for the door to open, and who can therefore anticipate the moment of opening. Only through mastering these skills, one could pass the door smoothly and after the first attempt.

Within this cluster, the users' heading is usually towards South and is changing in order to adequately approach the door. However, the consecutive changes of users' heading suggest continuous readjusting of their orientation, since the door seems to be approached from a wrong angle. These changes of heading occur usually in the vicinity of the door (i.e. 1–2 metres), when in fact one should look for the proper heading a bit earlier, and then maintain the constant heading without repeatedly changing it.

Another group of movement patterns belonging to this cluster involve successive changes of heading after the user has entered the smaller room. In other words, they represent attempts to acquire a larger view field immediately after the user has arrived in a new room, confirming the behaviour identified in cluster 1. However, this behaviour has been further refined by high spatial users (see cluster 2) who decided to choose a better location for performing such heading changing, namely in the main open area of the current room. A set of consecutive rotations performed in such a place provides a better view field, increasing the information about the room spatial layout. This enables user to see the entrance point from a different position, which help integrating it in the spatial representation.

Cluster 6 groups the best predictions which occurred on the ground, first and second floor, within the area enclosed by the black rectangle drawn in Figures 8.36, 8.37 and 8.38. This cluster has been identified as representing a poor rule and is a mirror cluster of the Cluster 4. Therefore, the observations made above apply to this cluster as well.

8.5.8 Rule Generalisation

The previously identified rules reflect some navigational strategies. One question which arises at this stage concerns their generalisation. Despite the fact that these rules have emerged by studying users' movement patterns on just one virtual building, it is claimed

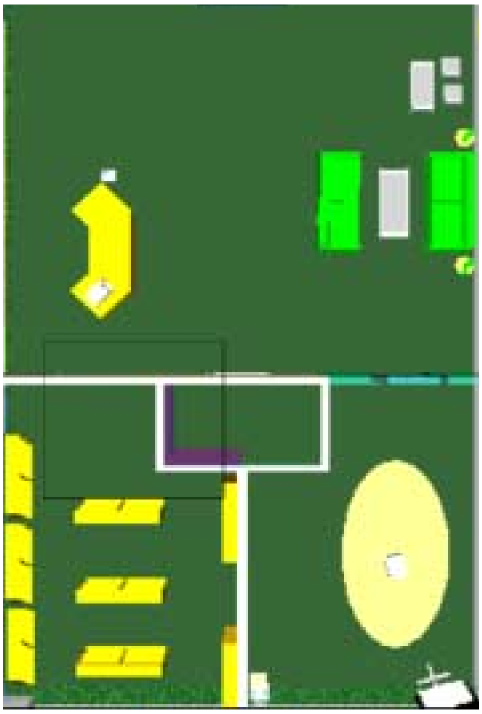


Figure 8.36: Cluster 6, Level 0

Figure 8.37: Cluster 6, Level 1

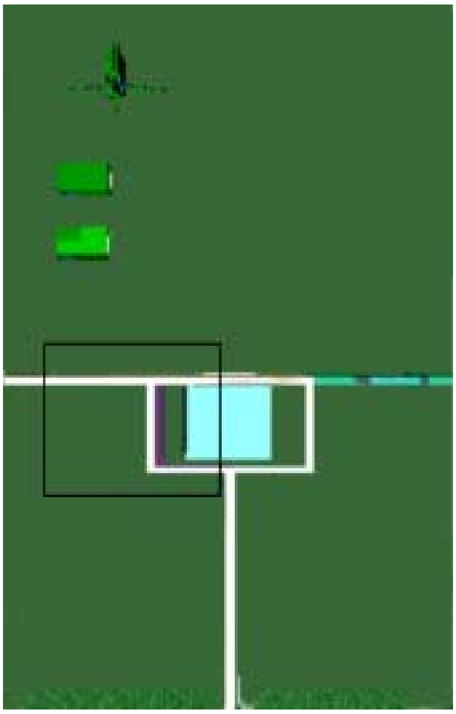


Figure 8.38: Cluster 6, Level 2

that these rules have a certain degree of generality. The ECHOES VE, through its four levels with different landmark configurations, offers a strong argument in this sense. Each rule has been described in relation to the floors it emerged from. The rules have been also interpreted in more general terms, searching for similarities among these floors and dissimilarities between them and those floors where the rules did not apply.

Of course, users could make some inferences about the spatial structure of the ECHOES VE, since all the levels belong to the same building. However, the presence of the virtual lift in the middle of the spatial layout, the rectangular shape of the entire spatial layout, the similar shape and size of the rooms located on the same areas of the spatial layout but on different levels are common-sense assumptions, which can be often encountered in the physical world. Therefore, it has been considered that this ECHOES-related specificity does not limit in any way the rule generalisation, and these rules could be used to infer, predict or understand users' behaviour in other spaces as well.

8.5.9 Conclusions

Two efficient procedural rules have been identified throughout this section:

- *Surveying zone* From the starting point, the users search for the nearby largest open area from where a larger view field enables them to acquire information about both spatial layout and landmark configuration.
- *Median paths* As long as none of the landmarks acts as a strong attractor, in other words none of the landmarks raises the user's interest, he/she will follow an *equilibrium path* between the nearby landmarks (this could also include walls). This rule resembles the "wall following" technique but it is more efficient. As soon as one of the landmarks captures user's interest, the equilibrium path is not followed anymore and the user gravitates towards this particular landmark, with minimum energy expenditure.

The inefficient procedural rule is related to the difficulties encountered by low spatial users in passing through the sliding doors. Through their design, these doors put unusual demands on these users. This rule is not primarily related to navigation, but suggests once again the importance of individual differences in designing VEs. These users lack some skills and in order to help them overcoming their limitations, the doors should be designed differently (see Chapter 11).

8.6 Summary

This work comes to fill a gap of research on individual differences in navigating in VEs. It focuses on investigating user mental models of navigation, in order to build a user model of navigation. The user model consists of a set of navigational rules which can support efficient spatial behaviour, and accordingly can be exploited for designing VEs for navigation assistance. The methodology employed for extracting these rules is based on techniques developed in the area of machine learning.

The machine learning approach for studying navigation looks promising. It led to two high-level rules or strategies, consisting of identifying the so-called *surveying zone* for performing efficient observation of spatial layout and landmarks' configuration, and following the *median paths* among nearby landmarks until one of them acts as an attractor. Another rule captures the difficulties encountered by low spatial users while passing through the virtual sliding doors. This latter result is primarily related to the limitations associated with the current design of ECHOES VE.

Findings indicate that there are individual differences in navigational patterns, which are related to the performance of spatial tasks, or in other words with users' spatial abilities. These results come to validate the working hypothesis. While high spatial users perform a good coverage of the space, by following a smooth path which resembles "going around the edge" of a feature, low spatial users navigate more erratically, performing more greater turns or crossovers. They seem to explore the environment in an unsystematic manner, which is reflected on navigation behaviour both on each level and across the levels.

Clustering trajectories allowed the identification of five trajectory clusters (Sas et al., 2003c) (Section 8.2), which in turn differentiate *good* and *poor* motion trajectories and their associated characteristics. Good–poor or efficient–inefficient have been determined in the light of users' performance on spatial tasks. The findings outlined reflect high level navigational rules which have been identified by analysing the top 10% predictions of RNN. These rules have considerable face validity, in the light of navigational models and theories presented in Section 3.2.3. These rules have been empirically identified and tested through the NN simulation.

Increasing the percent of best RNN predictions included in the rule extraction module could lead to a larger set of navigational rules. Additionally, increasing the sample size of study participants could provide more reliable results. An interesting study direction to be followed consists of extracting such rules, from trajectory paths performed in completely different VEs, where different variables regarding spatial layout and landmark configuration can be efficiently controlled and manipulated. Such study will help refining the currently extracted rules.

Finally, the purpose of capturing these rules consists of employing them in the design of adaptive VEs for navigation support (see Section 11.4). Such adaptive VEs can identify for example the low spatial users and adapt themselves in order to compensate the limitations of these users, which are reflected in inefficient spatial behaviour. The code source supporting this rule extraction process can be run in real-time and without human supervision, presenting also a valuable power of generalisation which is an inherent aspect of ANNs. The adaptive VE system can potentially learn new rules or refine the trajectory clusters, through the on-line navigation support offered to its users. The implementation, evaluation and exploitation of this generalisation potential constitute future directions of work.

In the attempt to increase the validity of the results presented in this chapter, a second approach of analysing user spatial behaviours has been employed. This ensures theoretical triangulation (see Section 5.5.1) which consists of employing different theories for data analysis and interpretation. As anticipated in Section 5.9, this additional approach will highlight new aspects, which were not captured by the machine learning approach. Searching for alternative ways to analyse trajectory paths, an increased attention received their geometric features. Comparing movement paths with some classic curves (i.e. circle, ellipse, parabola etc.), would offer a considerable advantage. Both machine learning and geometry approaches focus on the analysis of the spatial behaviours performed within the VE, and each of them strives to extract rules and strategies underlying such behaviours. The following chapter describes the second method and the findings obtained.

Chapter 9

Individual Differences in Navigational Patterns — A Curve Geometry Approach

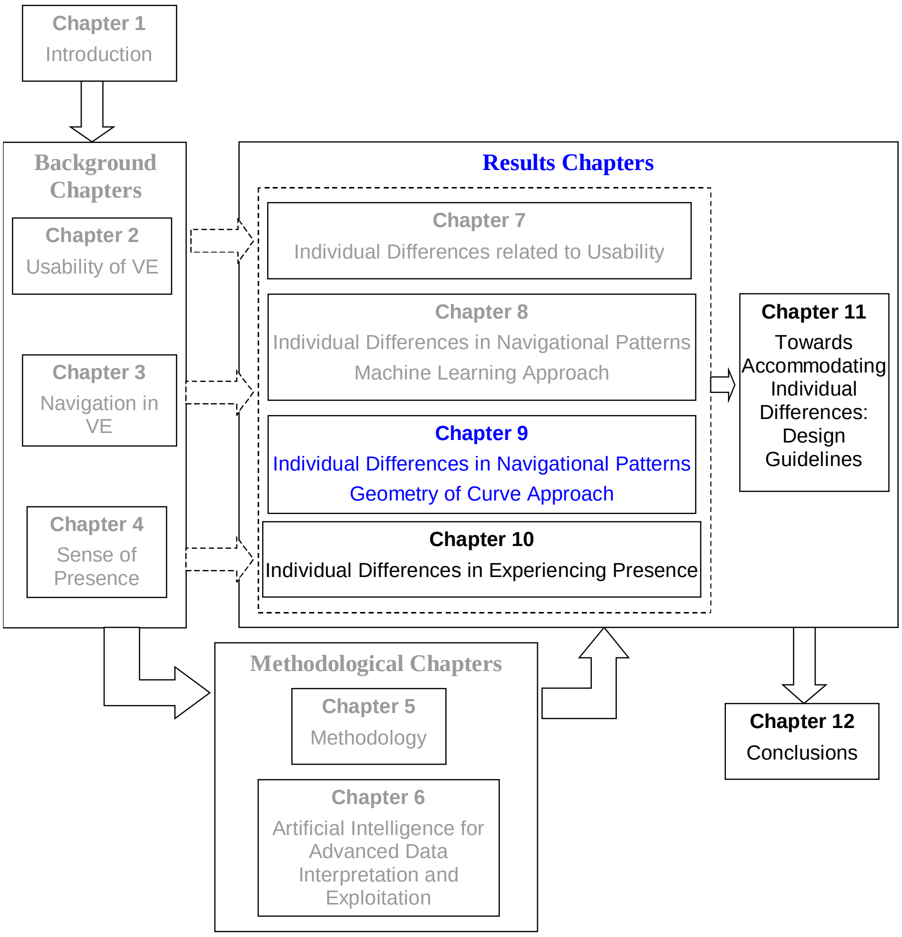


Figure 9.1: Road Map

9.1 Introduction

The results presented in Chapter 8 provided a set of high level rules or navigational strategies. In order to increase the validity of these findings, another complementary methodology for analysing user spatial behaviour has been employed. Searching for alternative methods of analysing movement trajectory, the geometric features of a user's paths appeared to be relevant. This gave rise to the idea of comparing movement paths with some prototypical curves, whose equation could predict a user's trajectory, thus offering a valuable support for rule extraction or navigation assistance. Consequently, the analysis of spatial behaviour has also been performed using an approach inspired by curve geometry.

In addition, such a method can provide an efficient diagnostic tool for differentiating users on the basis of their spatial behaviour. The potential of this methodology can be increased through relating the navigational patterns to user's performance on spatial tasks. Applying Bézier curves for modelling users' trajectories while they navigate within a Virtual Environment (VE), is another contribution of this thesis.

The analysis of spatial behaviour, whose theoretical foundation has been thoroughly introduced in Chapter 3, is performed in the light of providing guidelines for designing adaptive VEs able to accommodate individual differences in navigational patterns (see Chapter 11) and consequently to assist low spatial users in carrying out spatial tasks.

This chapter addresses the following two objectives, introduced in Section 1.3:

1. The investigation of individual differences in navigational patterns followed by users within the VE, and
2. The investigation of the rules and strategies underlying user spatial behaviour and the development of a user model based upon them.

It is conjectured that the specific characteristics of this methodology, complementing the machine learning approach described in Chapter 8, can lead to the extraction of other navigational rules.

This chapter starts by introducing the concept of motion analysis. It discusses the application of Bézier curves as a *curve fitting* technique, for motion analysis in fields like robotics and VEs. Furthermore, it is argued that employing Bézier curves in the context of this study represents an appropriate rule extraction methodology. The subsequent section describes the Bézier curves and introduces the concept of curvature. Finally, the impact of results for modelling users' spatial behaviour is discussed.

9.2 Motion Analysis

Motion analysis has been a topic of increased interest in a variety of fields from kinematics (Chaudhari et al., 2001; Sudarsky and House., 1998; Lim and Thalmann, 2001) to biomedical applications (Sühling et al., 2002), from ergonomics (Damsgaard et al.,

2001) to video surveillance (Grimson et al., 1998; Owens and Hunter, 2000). For a review and state of the art, see Aggarwa and Cai, (1997) and Perales et al., (2001).

Attempts to model motion trajectory has led to a large range of algorithms (Musto et al., 2000; Agrawala and Stolte, 2001; Lim and Thalmann, 2001). Bézier curves have been successfully applied for motion planning algorithms for robot navigation (Arakawa et al., 1995; Khatib et al., 1997) or automatic animation of virtual characters within VEs (Chung and Hahn, 1999; Pettre et al., 2002; Boulic et al., 1994). Despite their variety, these algorithms have a common feature: the trajectory is usually generated by a set of cubic Bézier curves smoothly joined, which pass through a set of points previously extracted (Shao and Zhou, 1996). For the endpoints selected according to some criteria, the algorithms compute the Bézier control points in between (Arakawa et al., 1995).

In the case of this thesis, the goal and consequently the approach is different and novel. It consists of the analysis of efficient and inefficient spatial behaviour, on the basis of the quantitative measurements, such as goodness of fit, curvature and number of inflexion points obtained from the Bézier curve fitting to users' original trajectories. Therefore, this approach did not employ cubic Béziers, but Béziers of high order, where the order has been dictated by the number of different consecutive locations of the original trajectory. To the best of my knowledge, such a methodology has never been used for analysing user spatial behaviour.

9.2.1 Conceptual Delimitations

Generalisation, a concept borrowed from cartography, is the process of simplifying the geometric representation of geographic features in order to eliminate less relevant details, while preserving the visual clarity of the map (Campbell, 1998). Generalisation techniques, excellently reviewed by McMaster (1992), are particularly used in digital cartography. The most significant benefit of the generalisation process is the increase in the amount of meaning, while reducing the amount of data.

Among the elements of line generalisation, relevant for this work is *smoothing* or angularity reduction which involves shifting the points in order to eliminate noise or irrelevant small changes in the direction of the path and to retain the significant trend (McMaster, 1990). The most common techniques for line smoothing, applied in Geographic Information System (GIS) have been classified into: running averages, least squares line fitting and piecewise spline curve fitting (McMaster, 1989; McMaster and Shea, 1992). *Curve fitting* tries to approximate a sequence of points, or even the whole line, with a continuous function (Hickey, 1994). In the context of this thesis, the polynomial curve fitting by Bézier curves has been employed.

9.3 Motivation

Since the major interest of this methodology consists of identifying those aspects separating efficient from inefficient strategies, the effect size[1] of study findings needed to be increased. In this case, the effect size will be an indicator of how big is the role of performance on search task in determining the navigational patterns (Gravetter and Wallnau, 1999; Heiman, 2001). There are three ways to create a more powerful design that can increase the size of the t score in t-test: maximising the difference between conditions, minimising the variability within each condition and maximising the sample in each condition (Heiman, 2001). Within the current study only the first solution is addressable, through statistical manipulation. This research has been carried out on two groups of trajectories performed by users, identified on the basis of their performance on the search task. These groups consisted of trajectories followed by the top 20% of users and bottom 20% of users, respectively.

A visual inspection of the trajectories within each group led to a series of qualitative observations regarding the differences between them, in terms of trajectory "smoothness", numbers of turns and degree of turning angles. It is conjectured that these issues can constitute a basis for discriminating efficient from inefficient navigational strategies.

In order to identify some indicators related to trajectory properties, trajectory motion analysis was employed. This technique offers a comprehensive, quantified and statistically grounded understanding of the aspects characterising high versus low spatial users. For the purpose of this thesis, the smoothing technique was chosen. To summarise, the choice of Bézier curve fitting is motivated by several factors:

1. Smoothing the trajectory path. Visual inspection suggested that good trajectories are characterised by a higher degree of smoothness, for example less or smaller zigzags than those present in poor trajectories. This requires a trajectory representation which could measure the degree of smoothness, or in other words, a differentiable curve equation.
2. Continuous versus Discrete representation. The present shape of trajectories is rather coarse, since points have been recorded for movements greater than half a virtual metre, and for each turn greater than 30 deg. Fitting a Bézier curve to each trajectory is intended to overcome the coarse data gathered through an event-based process (rather than time-based process). The higher granularity, employed by curve fitting, offers a suitable model of the trajectory, preserving in the same time its shape. In addition, it allows the computation of goodness of fit and curvature on each point of the curve.
3. Quantitative measurements. Fitting a Bézier curve to each trajectory offers additional benefits in terms of quantitative measures, such as goodness of fit, curvature

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[1] Effect size is the proportion of variance accounted for in an experiment, which indicates how consistently differences in the dependent scores are influenced by changes in the independent variables (Heiman, 2001).

and number of inflexion points.

9.4 Bézier Curves

A Bézier curve is a polynomial defined by a set of *control points.* The first and the last point are called *endpoints.* This type of curve has been developed by Pierre Bézier three decades ago for improving the shape design of the Renault car. Nowadays, Bézier curves have a large applicability in computer graphics (Knuth, 1986) and in particular in the Adobe PostScript (1985) drawing model.

The distinction between endpoints and control points is related to the different roles played by these points, in terms of location and shape of the curve. The endpoints anchor the ends of the curve, while the control points determine the actual shape of the curve, acting like magnets that pull the curve. Therefore, given these two types of points, a Bézier curve passes through the endpoints and is tangential to the first and last side of the open polygon defined by its points (Marsh, 1999).

Probably the most widely used form of Bézier curve is the one based on cubic polynomial equations. It is defined by four points: two endpoints $P_0(x_0, y_0)$, $P_3(x_3, y_3)$ and two control points $P_1(x_1, y_1)$, $P_2(x_2, y_2)$ (Figure 9.2).

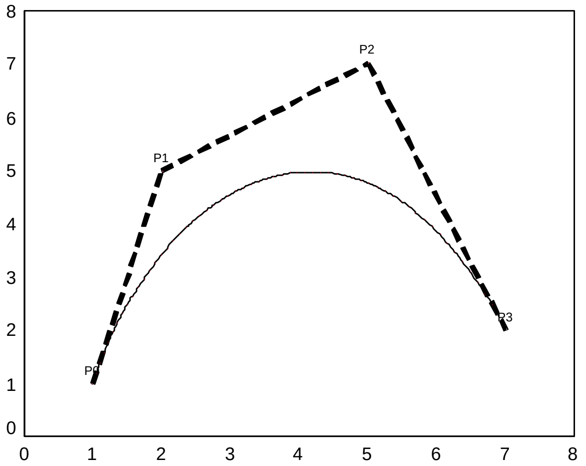

Figure 9.2: Cubic Bézier Curve

The parametric equations are:

$$\begin{aligned} x(t) &= (1-t)^3 x_0 + 3t(1-t)^2 x_1 + 3t^2(1-t) x_2 + t^3 x_3 \ , \\ y(t) &= (1-t)^3 y_0 + 3t(1-t)^2 y_1 + 3t^2(1-t) y_2 + t^3 y_3 \end{aligned} \tag{9.1}$$

The parametric equation of a Bézier curve of order n is given by:

$$B(t) = \begin{bmatrix} x(t) \\ y(t) \end{bmatrix} = \sum_{k=0}^{n} C_n^k \cdot (1-t)^{n-k} \cdot t^k \cdot P_k \ , \tag{9.2}$$

where t is the parameter of the curve $(0 \leq t \leq 1)$ and P_k are constant vectors associated with control points (including the endpoints). C_n^k are binomial coefficients:

$$C_n^k = \binom{n}{k} = \frac{n!}{k!(n-k)!}, \quad 0 \leq k \leq n. \tag{9.3}$$

The number of points determining a Bézier curve defines the degree of the associated polynomial.

9.4.1 Properties of Bézier Curves

The properties of Bézier curves are summarised below (Bartels et al., 1998):

1. *Endpoint interpolation.* A Bézier curve usually does not pass through the intermediate control points but it will always interpolate the endpoints. However, the order and position of the control points impact on the shape of the curve.
2. *Affine invariance.* An affine transformation applied to the initial set of points generates a Bézier curve which is the result of the same transformation applied to the original curve.
3. *Convex hull property.* Bézier curve lies in the minimal convex enclosure of its points.
4. *Linear precision.* If the control points belong to a straight line, the Bézier curve will be a straight line as well.
5. The curve is continuous and differentiable.

The major limitation of this approach is that high order Bézier curves, as any high order polynomials, are vulnerable to problems of numerical instability. Consequently, this issue is discussed in more detail in the following section.

9.4.2 Numerical Instability

Numerical instability is detected when a numerical scheme stops behaving like the analytic solution, and is due to the imprecision of floating point arithmetic, rounding errors or growing solutions outside the range of values which can be handled by the computer (Lander, 2003). In order to prevent and identify whether this problem occurred in the case of Bézier curves, the following measures have been taken:

- Data normalisation. All the coordinates were normalised to the range $(-1, 1)$.
- Using two Bézier representations. In an attempt to duplicate the Bézier representation and therefore to check the similarity of the results, in addition to the curve generated through equation 9.2, the Bézier curves described by the following equation 9.4 (Zhang and Li, 1998) have been also generated.

$$B(t) = \sum_{k=0}^{n} \mathrm{b}_k \cdot t^k \ , \tag{9.4}$$

where t is the parameter of the curve ($0 \leq t \leq 1$) and b_k are coefficients described by:

$$\mathrm{b}_k = \begin{bmatrix} x \\ y \end{bmatrix} = \sum_{i=0}^{k} (-1)^{k-i} C_n^k \cdot C_k^i \cdot \mathrm{P}_i \tag{9.5}$$

The curve fitting routines have been run for both Bézier curve equations. Equation 9.2 generated results within the expected range $(-1, 1)$. However, the routines based on equation 9.4 produced results outside the specified range, for the high orders. For orders higher than 450, the numerical instability could be clearly detected.

- Plotting curves. The generated Bézier curves were plotted together with the original trajectories. A visual inspection confirmed the face validity of these results. It suggested that the numerical instability for the representation offered by the equation 9.2 does not cause any serious problems.
- Polynomial order effect. An additional test was performed in order to check for any traces of numerical instability generated by the equation 9.2. If equation 9.2 leads to numerical instability than this will be more noticeable for long trajectories, and accordingly the generated Bézier curve will poorly approximate long trajectories. No statistically significant differences were found between the goodness of fit (see Section 9.5 for a detailed description), for the long trajectories (passing through more than 71 control points) compared to the short trajectories.

To conclude, the curve fitting routine based on the equation 9.2 is not affected by numerical instability.

9.4.3 Curvature

Curvature is a mathematical concept which measures the bending properties of a curve. A linear segment of a curve has a curvature of zero, while the sharper the curve bends, the higher the curvature is. Therefore, curvature offers both an intuitive description of the shape of the curve and numerical values for each of its points.

Curvature of a plane curve at a given point P is the inverse at the radius of the *osculating circle* ($\kappa = 1/r$), the circle which shares the same tangent as a curve at a given point (Gray, 1998). The most common type of curvature is the *extrinsic curvature*, whose equation is as follows (Gray, 1998):

$$\kappa[t] = \frac{x'(t) \cdot y''(t) - x''(t) \cdot y'(t)}{(x'^2(t) + y'^2(t))^{3/2}} \tag{9.6}$$

The extrinsic curvature cannot be detected by someone who cannot observe the three-dimensional space surrounding the surface on which he resides. It is the *intrinsic curvature* which is detectable by the "inhabitants" of a surface and not just outside observers (Weisstein, 2003).

9.5 Results

A comprehensive set of data was recorded throughout the experiment, by a rich set of virtual sensors together with an odometer and a rotational event listener (Delahunty, 2001) (see Section 5.8). The data captured when the user interacts with the ECHOES virtual space contain details of navigation paths along the temporal dimension. The motion trajectories for the exploration phase were recorded as bivariate time series of (x, y) Cartesian coordinates, and represented in a form of a polygon connecting these points. Analysis was carried out for 19 trajectories. The average number of different positions (translations) in each trajectory is 71. The shortest trajectory is represented by 29 different locations while the longest one is represented by 125.

The motion analysis involved a comparison between the two groups of users with respect to the properties of the Bézier curves approximating the trajectories. Indicators such as goodness of fit, curvature and inflexion points are discussed in the following subsections. The entire analysis was carried out to emphasise the differences that underlie the two distinct spatial behaviours: *poor* and *good.*

9.5.1 Goodness of Fit

Goodness of fit was assessed by computing the residual(s), namely the shortest distance from each point of the trajectory to the curve (Bock and Krischer, 1998). The Bézier curve is represented by a pre-computed set of points, 20 points for each original trajectory point. The shortest distance is not necessarily the global minimum and therefore, for each point of trajectory, its "correspondent" point of the curve has to be located (Figure 9.3).

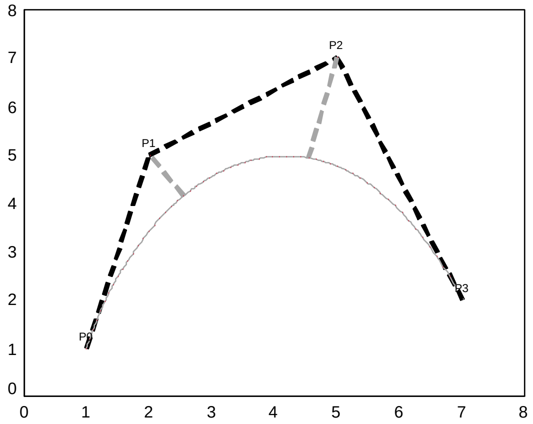

Figure 9.3: Distances to Bézier Curve

To compute the shortest distance the following method (Algorithm 7) was used. The algorithm searches within a window employing at least two consecutive points from the Bézier curve. This ensures that for a particular trajectory point, the first local minimum of its distance to the curve is kept as a solution. The residual values

Algorithm 7 Goodness of Fit

```
Require: $P_k$ vectors associated with trajectory control points, $0 \leq k \leq n$ and $B_t$
    associated with Bézier curve points, $0 \leq t \leq 20n$
Ensure: shortest distance $Distance_k$ from trajectory points to the curve
indexmin ⇐ 0
$Distance_k \Leftarrow 0$
for all $P_k$ do
    for $t = indexmin$ to 20n do
        $dist_t = ((B_t.x - P_k.x)^2 + (B_t.y - P_k.y)^2)^{1/2}$
        $dist_{t+1} = ((B_{t+1}.x - P_k.x)^2 + (B_{t+1}.y - P_k.y)^2)^{1/2}$
        if $dist_t \leq Distance_k$ AND $dist_t < dist_{t+1}$ then
            $Distance_k = dist_t$
            $indexmin = t$
            break
        else
            $t = t + 1$
        end if
    end for
end for
```

range between the 0.000215 and 0.318933, having a mean value of 0.055 and a standard deviation of 0.049. The t-test performed on the residuals obtained by the two groups of trajectories shows significant differences ($t(1330) = 5.02$, $p < 0.001$). The average distance from the original trajectory points to the generated Bézier curve is significantly smaller for good trajectories (Mean = 0.047) than for poor trajectories (Mean = 0.061). Because the Bézier curve can be seen as a "smoothening" of the original trajectory, this finding supports the idea that good trajectories are significantly smoother than poor trajectories.

The following figures present four examples of users' trajectories, together with the Bézier curves which have been generated for each of them. For illustration, two of those trajectories have been chosen among the poor ones (Figures 9.4 and 9.6), while the other two among the good ones (Figure 9.5 and 9.7).

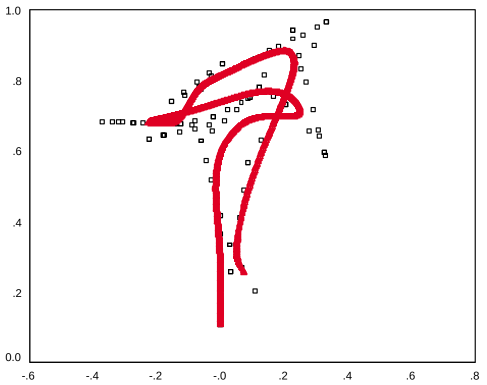

Figure 9.4: Original Trajectory and Bézier Curve of a Poor User (Female)

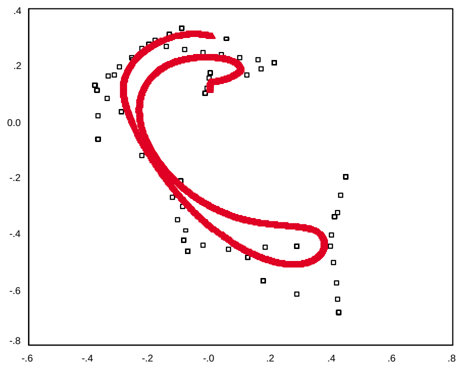

Figure 9.5: Original Trajectory and Bézier Curve of a Poor User (Male)

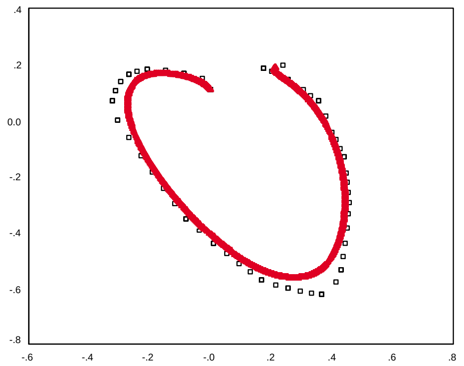

Figure 9.6: Original Trajectory and Bézier Curve of a Good User (Female)

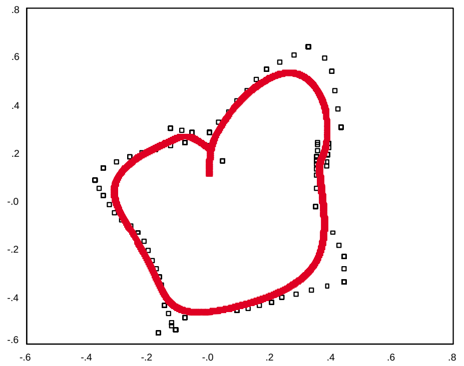

Figure 9.7: Original Trajectory and Bézier Curve of a Good User (Male)

9.5.2 Curvature

The curvature was calculated for each of the pre-computed points of the Bézier curves, namely 20 Bézier points for each point of the original trajectory. Curvature values ranged between -473346 and 7253.518. After removing the outliers and extreme values which represented about 15% of the processed data set, the remaining curvature values lie within the range $(-10, 10)$.

The absolute value of the curvature is significantly higher for poor trajectories as compared to good trajectories ($t(24488.21) = 9.45$, $p < 0.001$). The average absolute curvature per each point of Bézier curves generated for poor trajectories is higher (Mean $= 3.61$) than for those generated for good trajectories (Mean $= 3.25$).

A detailed analysis of the curvature on each point of Bézier curves, fitting poor and good trajectories, involved comparing their distributions. The Bézier curves approximating good trajectories provide significantly more curvature values within the ranges $(-7, -6)$ and $(-4, -1)$. The Bézier curves approximating poor trajectories give significantly more curvature values within the ranges $(-1, 1)$ and $(2, 8)$ and as mentioned above for the values smaller than -10 and greater than 10.

The clustered histograms in Figure 9.8 present the frequencies of the curvature values for the two groups of users. Since the extremes are omitted, the values are within the range $(-10, 10)$. As it is shown, the high curvature values characterising poor trajectories have higher frequencies than the ones for the good trajectories, except for the curvature values close to zero. In other words, users employing good strategies perform more small rotations than low spatial users. The latter rotate more often at greater angles. This analysis of rotational behaviour is further detailed in Section 9.5.4.

It seems that very small curvature values, within the range $(-1, 1)$ are the ones associated with noise (i.e. small zigzags), while large curvature values reflect sharp bends along the trajectories. Thus, poor trajectories are particularly characterised by both these features: small zigzags and sharp angles.

An interesting aspect suggested by this analysis reflects the tendency of good tra-

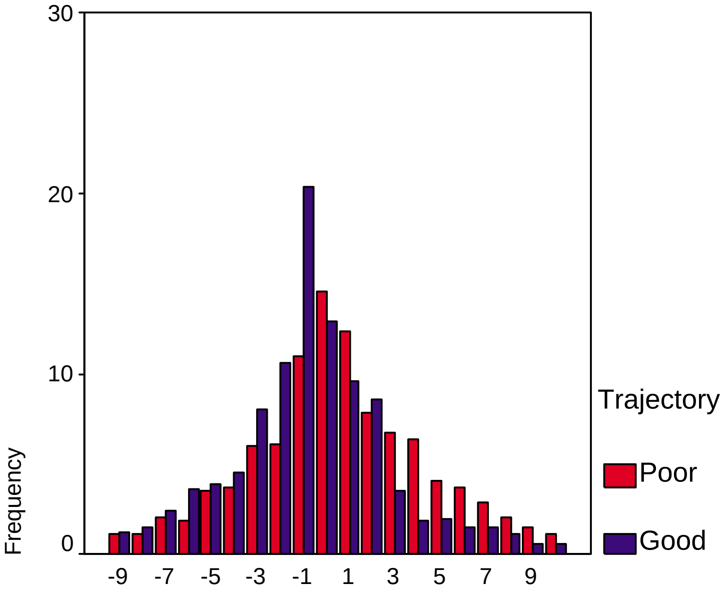

Figure 9.8: Curvature Histogram of Bézier Curves Approximating Users' Trajectories

jectories to contain more curvature values with negative sign, as opposed to poor trajectories which can be better characterised by curvature values of positive sign. Positive curvature values indicate a turn to the left, while a negative curvature values indicate a turn to the right. In other words, good trajectories contain more turns to the right, while poor trajectories contain more turns to the left.

The analysis of the curvature values with their signs has indicated that low spatial users' trajectories present significantly higher positive curvature values (Mean = 107.69) than high spatial users' trajectories (Mean = 57.60), ($t(2203.40) = 3.81$, $p < 0.001$). At the same time, significantly more outliers, or curvature values higher than 10 or smaller than -10, belong to poor trajectories, namely more than 60% of the negative outliers and more than 73% positive outliers (continuity correction: $\chi(1) = 72.93$, $p < 0.001$). The analysis concerning the sign of the curvature is continued in the following subsection, dedicated to the inflexion points.

9.5.3 Inflexion Points

The number of inflexion points, where the curvature sign changes, offers another indicator which differentiates between good and poor trajectories. Findings show that trajectories followed by low spatial users contain a significantly higher percent of inflexion points than good trajectories, ($t(12) = 2.96$, $p < 0.01$). In other words, good trajectories are characterised to a great extent by constant curvature sign.

Once again, if the sign of the curvature is taken into consideration, low spatial users' trajectories contain a higher percent of points where the curve turns to the left, while good trajectories contain a higher percent of points where the curve turns to the right ($t(12) = 1.80$, $p < 0.05$). I conjecture that a possible explanation for these results, could be related to the “left to right” perceptual organisation, rooted in the western convention of reading.

The following Sections 9.5.4, 9.5.5, 9.5.6 and 9.5.7 focus on other aspects of interest in supporting further differentiation between efficient and inefficient navigators’ trajectories (Sas et al., 2004a). They are related to the rotational, translational and around-landmarks behaviour, and to the area covered by the users during navigation. These results have been obtained by analysing the raw data and not the points generated by the Bézier curves.

9.5.4 Rotational Behaviour

Given the significance of rotations along a movement path, a further analysis has been performed in order to identify more differences which discriminate efficient from inefficient spatial behaviour. Each action performed by the user is either a rotation or a translation. Rotations receive increased attention, since they represent those joints, where trajectory segments are articulated at different angles. The location where rotation is performed and the rotation angle provide valuable information about the user’s orientation and user’s intentions. This justifies the following analysis.

Each angle performed at a particular location, possibly consisting of one or more successive rotations, has been computed and averaged for each user. This angle was called *observational angle* since it allows the user to observe the environment through the increased view field it facilitates. Figure 9.9 presents a sample of user’s behaviour, where P_1, P_2 and P_3 represent three consecutive positions in time, while θ_1, θ_2 and θ_3 represent there consecutive changes of heading, carried out at location P_2.

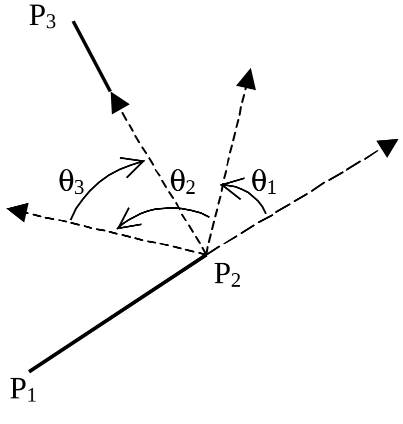

Figure 9.9: Observation Angle

The observation angle was computed as follows:

$$\text{Observation angle} = \sum_{i=1}^{k} |\theta_i| \,, \tag{9.7}$$

where k is the number of successive rotations (in our example $k = 3$).

A t-test suggests a significant difference between the values of these angles corresponding to rotations performed by efficient versus inefficient users. Thus, low spatial user perform significantly higher changes of heading (Meanabove65 deg) compared to high spatial users (Meanbelow45 deg) ($t(12) = 1.92$, $p < 0.05$).

When the sign of the rotation angle has been also considered, another angle indicator was obtained. It represents the angle between two adjacent segments of trajectory which suggests a change of direction between two translations. Such an angle is caled *moving angle* and differs from the previous indicator when users change the rotation direction within a set of consecutive rotations. Such a *moving angle* between consecutive translations performed at different headings is equal or smaller than the *observational angle.*

Figure 9.10 presents the same sample of user's behaviour as that depicted in Figure 9.9, where the moving angle is the angle θ_4.

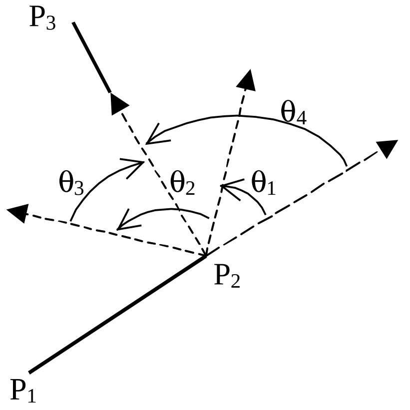

Figure 9.10: Moving Angle

Findings suggest that low spatial users performed significantly higher changes of heading (Mean above 50 deg) when measured as *moving angles*, compared to high spatial users (Mean below 35 deg) ($t(12) = 1.83$, $p < 0.05$). Looking at the distribution of these angles, it appeared that low spatial users performed significantly more rotations higher than 90 deg (61.2%), compared to low spatial users (38.8%) (continuity correction: $\chi^2(1) = 20.71$, $p < 0.05$).

The analysis of spatial behaviour with respect to the number of rotations and translations within the entire set of trajectories, revealed another interesting funding. On average per trajectory, high spatial users performed a significantly higher number of rotations (Mean = 12.07) than low spatial users (Mean = 10.36) ($t(11178) = 10.98$, $p < 0.001$). When this analysis was narrowed to the numbers of *successive rotational steps* performed between two translations, it appeared that high spatial users performed significantly less such kind of consecutive rotations (Mean = 2.23), compared to low spatial users (Mean = 3.01) ($t(10947) = 9.93$, $p < 0.001$).

9.5.5 Translational Behaviour

High spatial users performed also significantly less consecutive translations (Mean = 1.60) than low spatial users (Mean = 1.80) ($t(11514) = 3.92$, $p < 0.001$). High spatial users performed also significantly more translations per trajectory (Mean = 11.97) compared to low spatial users (Mean = 10.26) ($t(11192) = 10.90$, $p < 0.001$). In addition, the length of each straight line segment, namely the distance covered through consecutive translations, was measured along each trajectory. Such segments have been obtained as a result of consecutive translations performed by the user. A t-test indicated significant differences with respect to the average length of the straight line segments followed by high spatial users (Mean = 2.94) as opposed to those followed by low spatial users (Mean = 3.82) ($t(12) = 2.49$, $p < 0.05$).

9.5.6 Behaviour Around Landmarks

An important aspect related to translations refers to behaviour around landmarks. Are there any differences in the way efficient and inefficient navigators visit or revisit landmarks, in the way they navigate along a given landmark, or to what distance from the landmarks of interest they navigate? These are the kind of questions that this section tries to answer. Without being statistically significant, low spatial users visit less landmarks (Mean = 11.25) than high spatial users (Mean = 16.27) ($t(12) = 1.50$, $p > 0.05$). An important outcome suggests that low spatial users revisited significantly more time the same landmarks (Mean = 6.53), as opposed to high spatial users (Mean = 3.60) ($t(12) = 2.95$, $p < 0.05$). Without reaching significance, other findings suggest that high spatial users visited more rooms (Mean = 9) than low spatial users (Mean = 6.93).

Findings also indicates that high spatial users move along the nearest landmarks, those which act as attractors, significantly longer (Mean = 20.88 events), compared to low spatial users (Mean = 14.31 events) ($t(12) = 1.97$, $p < 0.05$). T-test analysis indicates that low spatial users move along the landmarks of interest at significantly longer distances (Mean = 1.92), compared to high spatial users (Mean = 1.68) ($t(12) = 1.95$, $p < 0.05$). This implies that the search performed by high spatial users is more systematic, focusing thoroughly on one landmark at the time. Once a particular landmark acts as an attractor and a complete search has been performed in its vicinity, the need for revisiting it decreases significantly.

There is no significant difference between trajectories performed by high versus low spatial users in terms of the trajectory length. Given this result, it will be interesting investigating whether the same relationship holds with respect to the area covered by high and low spatial users.

9.5.7 Area Enclosed

The area enclosed by the polygon, connecting each point from the movement path is considered for each motion trajectory. The points were connected in an order similar with the one in which they were reached, namely each point with the one that follows. The very last point was considered to be connected to the first point.

The computation of the enclosed area was carried out through the method described by the Algorithm 8. Testing whether a point is inside a polygon was carried out using the *ray tracing* method (Shimrat, 1962; Haines, 1994). The ray tracing method consists of computing how many times a ray shot from a given point crosses the polygon. If this number is even, than the testing point is outside the area surrounded by the polygon, whereas if it is odd, the point is inside this area.

For computing the enclosed area, each point of the polygon has been projected on a horizontal line below the lowest point of it. The enclosed area associated with each segment is composed of a rectangle and a triangle. The entire area is computed by summing up the enclosed areas associated with each segment. The areas outside the polygon cancel as the polygon loops around to the beginning (Bourke, 1998). An example of the outcome provided by the Algorithm 8 is presented in the Figure 9.11.

Algorithm 8 Enclosed Area

```
Require: $P_k$ vectors associated with trajectory control points, $0 \leq k \leq n$ and $B_t$
    associated with Bézier curve points, $0 \leq t \leq 20n$
Ensure: area enclosed by the trajectory polygon
for $k = 0$ to 2 do
    $Polygon[k] = P_i[k]$ {Initialising the polygon}
end for
$lineindex = 3$
for $k = 3$ to $n$ do
    if $P_i[k]$ is not inside of the convex hull of $Polygon$ then
        $Polygon[lineindex] = P_i[k]$ {add point to $Polygon$}
    end if
    $lineindex = lineindex + 1$
    for $i = 0$ to $lineindex$ do
        if $P_i[k]$ is inside of the convex hull of the Polygon then
            remove $P_i[k]$ from the Polygon
        end if
    end for
    reorder the points from the Polygon to be consecutive
    compute the enclosed area
end for
```

Findings indicate that area enclosed by the points of good trajectories is significantly larger than the area enclosed by the points of poor trajectories ($t(12) = 2.96$, $p < 0.01$). In other words, high spatial users cover a significantly greater area than low spatial users.

9.6 Discussion

Results of this study validate the hypothesis regarding the differences between the two groups of trajectories identified on the basis of user performance. To summarise, poor

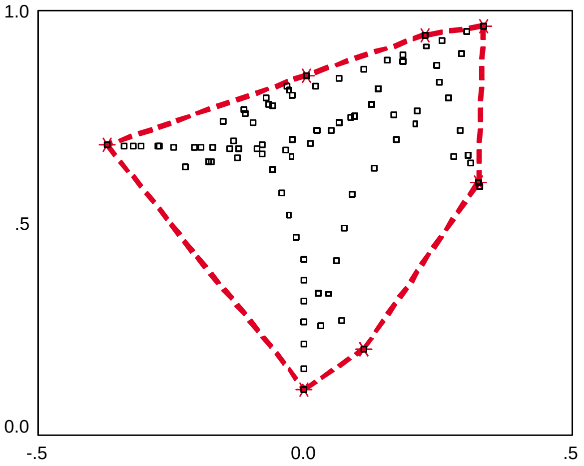

Figure 9.11: The Area Enclosed by a Poor Trajectory

trajectories have significantly more noise and are less smooth than good trajectories. Poor trajectories are also characterised by more turns at sharp angles, more changes of direction and significantly more straight line segments. In addition, they cover significantly smaller areas than good trajectories do.

The analysis of these results led to two major aspects strongly related to navigation performance. These are minimum energy principle and spatial orientation, and on both of these aspects high spatial users surpass the low spatial users.

9.6.1 Minimum Energy Principle

The key outcome of this study is that compared to inefficient spatial behaviour, the efficient spatial behaviour can be interpreted as an example of the *Minimum Energy Principle*. The minimum energy principle expresses itself through those procedural and strategic rules which enable users to achieve the goals with a minimum investment of resources, both temporal and cognitive (Warnett and McGonigle, 2002). There are two levels of which efficient spatial behaviour can be interpreted according to the economy principle or rational spending of resources.

At a macro level, high spatial users strive to cover the greatest possible area which would allow them to see/explore as much as possible with minimum resource consumption. In other words, they look for a better ratio $\frac{EnclosedArea}{TrajectoryLength}$. In fact, according to this composite criterion of performance, a significant differences appears again between high and low spatial users ($t(12) = 2.53$, p <0.01).

The efficiency of spatial behaviour performed by high spatial users is reflected also in the fact that these users try to grasp the entire picture, rather than focusing on its details. Thus, they visit each level of the building, usually in a systematic manner, then they visit more rooms and within the rooms, more landmarks than low spatial users do. These users are interested in acquiring a larger and more synthetic view of the virtual building, rather than an analytic one. Such a top down approach of exploring the virtual building is complemented by a thorough search in the vicinity of each landmark of interest.

At a micro level, the minimum energy principle is directly related to the *curve of least energy*. The shape taken by a thin beam is the one minimising its internal strain energy, which is proportional to the integral of the square of the curvature (Horn, 1983). Since good trajectories are defined by smaller absolute curvature values, they are closer to minimal energy curves than the poor trajectories. In a similar vein, the better goodness of fit of good trajectories with respect to the associated Bézier curves, suggests the reduction of needless expenditure of energy. Moreover, the smaller number of straight line segments along good trajectories reinforce the minimum energy principle, by allowing high spatial users to cover a larger area.

In addition, the way in which high spatial users search around landmarks differs from that employed by low spatial users. The same holistic approach employed at a macro level can be identified: high spatial users perform a thorough search around the landmarks which are considered of interest. They perform significantly more translations and rotations around these landmarks, at shorter distances and accordingly, they revisit these landmarks less.

9.6.2 Spatial Orientation

The second major aspect of these findings is related to spatial orientation. Spatial orientation refers to users' knowledge of position and orientation within the VE (Bowman et al., 1999; Bowman, 1999) (see Section 3.3.2). High spatial users succeeded in maintaining a better spatial orientation. Their spatial behaviour seems to be governed by a simple set of rules. They usually maintain the same main direction or steady orientation, only smoothly altered through small turns. They avoid both long straight movements and large changes of direction, thus maintaining the course of movement.

On the other hand, trajectories performed by low spatial users contain more turns of high curvatures. These users change their direction not only more often but also more drastically, with serious negative impact on their spatial orientation. This comes to validate the theoretical and experimental results from environmental psychology, and in particular related to spatial cognition (see Chapter 3).

The rotational behaviour of low spatial users presents several major limitations. These users rotate more often at angles greater than 90°, for both observing and changing the movement orientation. They perform significantly more consecutive rotations which dramatically increase the risk of disorientation.

Findings suggest that high spatial users carry out significantly more rotations and translations along a trajectory (on average 12 as opposed to 10), but significantly less such consecutive events (on average 2 rotations as opposed to 3). The actions of high spatial users seem to be more frequent, evenly distributed in time, and much smaller (both in changing the heading and changing the location). This is an important outcome which explains how the efficient navigators are more successful in maintaining their orientation and subsequently acquire better spatial knowledge.

9.7 Summary

This chapter, together with the previous one (Chapter 8) offer two original methodologies for investigating individual differences in navigating in VEs. Focusing primarily on user mental model of navigation, these approaches try to build a user model of navigation in VEs. Such a model is primarily defined through a set of navigational rules which accordingly can support efficient spatial behaviour (see Chapter 11).

While Chapter 8 described a methodology on the basis of techniques developed in the area of machine learning, this chapter proposes the use of Bézier curves for studying and modelling motion trajectories. Findings suggest that the first approach leads to high-level rules or navigational strategies, while the latter approach enables the formulation of some low-level rules. It is necessary to mention that the extraction of high-level rules has been enabled by the machine learning techniques employed, which elicited particularly the implicit knowledge embedded in navigational patterns.

Bézier curves provide a good fit to the data, and the results also indicate that the method provides a basis for the diagnosis of inefficient navigational patterns. The method offers two indicators: goodness of fit and average curvature which the study results indicate that carry important information about user performance, specifically in terms of spatial knowledge acquisition.

Findings indicate that there are individual differences in navigational patterns, which are related to performance on spatial tasks, or in other words with users' spatial abilities. These results come to validate the working hypothesis. Efficient spatial exploration can be defined by smooth trajectories, maintaining the movement direction and avoiding sharp angles. Curves are preferred to straight lines, and the greater the enclosed area, the better the performance. Low spatial users significantly violate the Principle of Least Action which advocates the reduction of needless expenditure of energy. They are inefficient and their frequent changes of direction increase the risk of disorientation.

Apart from offering a better understanding of spatial behaviour performed within VEs, in terms of individual differences in spatial knowledge acquisition, the study findings have a significant potential for practical applications. Differentiating between efficient and inefficient spatial behaviour and their underlying strategies could be exploited through applications dedicated to improving spatial skills, such as adaptive VEs.

This chapter ends the discussion of findings regarding individual differences in navigating within VEs. The following chapter presents the findings regarding individual differences in experiencing presence.

Chapter 10

Individual Differences in Experiencing Presence

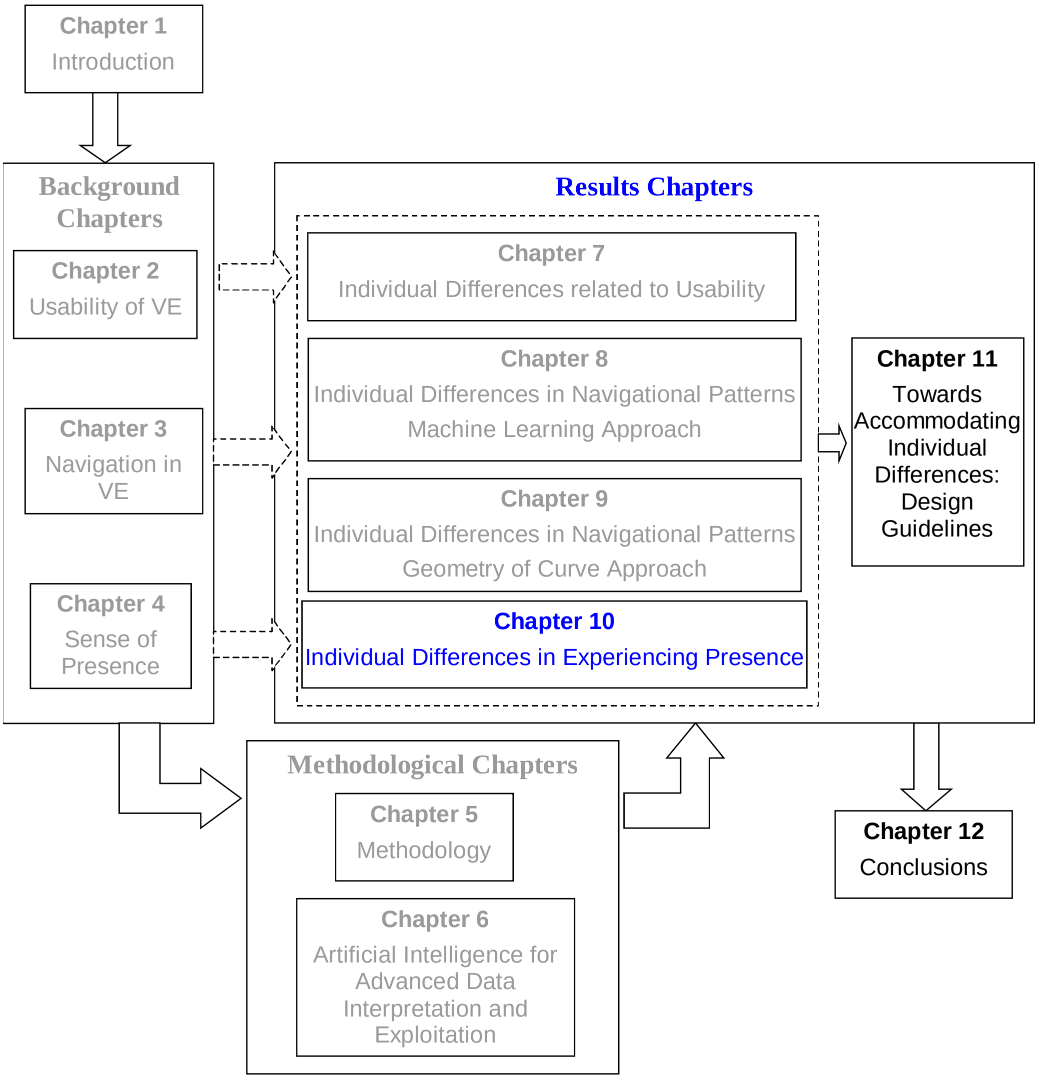

Figure 10.1: Road Map

10.1 Introduction

Psychological approaches to the study of presence are rare, and those with experimental support are even more limited. This thesis attempts to highlight the user characteristics which may lead to a better understanding of individual differences in relation to the experience of presence. Within this chapter the relationship between presence and personality factors such as absorption, creative imagination, empathy, willingness to experience presence and personality cognitive style is investigated. For a review of these factors see Section 4.3.2, while the presence construct has been introduced in Chapter 4. Such an analysis of personality factors impacting on presence provides both theoretical and practical benefits. Apart from expanding our understanding of presence, it could suggest various ways to accommodate the identified individual differences for increasing user's sense of presence in Virtual Environments (VEs). This chapter addresses the following objectives, introduced in Section 1.3:

1. The investigation of individual differences which impact on the level of sense of presence, and
2. The investigation of the relationship between presence and task performance.

Within this chapter, attention is given to a set of individual differences impacting on presence. This study design takes the shape of a quasi-experiment, where the quasi Independent Variables (IVs), can be statistically manipulated. Thus, participants are assigned to a particular condition because they already qualify for that condition, such as more empathic or less empathic; more absorbed or less absorbed (see Section 5.6). The quasi IVs are empathy, fantasy, creative imagination, absorption, willingness to experience presence and the four dimensions of personality cognitive style. By statistical manipulation, this work aims to investigate the effect of these variables on the level of sense of presence, which represents the Dependent Variable (DV). With respect to previously outlined objectives, the following working hypotheses were formulated:

- H1. The more empathic the users are, the more heightened will be their sense of presence.
- H2. Among empathy subscales, the fantasy subscale will be the most influential on presence.
- H3. The more absorbed subjects are, the heighten sense of presence they will experience.
- H4. The more creative imagination individuals can exhibit, the more sense of presence they will be able to experience.
- H5. The more willing to experience presence, the more presence users will experience.
- H6. Different dimensions of personality cognitive style impact on the experience of presence.

- H7. Different dimensions of personality cognitive style impact on the relationship between presence and task performance.

It would be useful to reopen the distinction between non-immersive and immersive VEs introduced in Section 2.3.1. While immersive VEs involve the restriction of users' senses in terms of their reference to the real world, the non-immersive VEs, or desktop VEs, do not restrict users' senses in any way (Fernie and Richards, 2002). Within immersive VEs, most of the users become immersed, despite the intragroup variability based on human factors. It is conjectured that in this case, presence is experienced because of the advanced technological aspects featured by these fully immersive systems. These technical issues are so impressive that they simply prevail over the human determinants of presence.

On the other hand, within non-immersive VEs whose technological infrastructure is less advanced, the user's experience of presence is mainly due, not to system characteristics, but rather to the associated human factors (Bowers et al., 1996). Since this study focuses on the impact of human factors upon presence, the choice of ECHOES — a desktop VE — as a suitable experimental testbed is justified.

Another useful distinction to be made is the one between trait and state (Allport, 1966). It can help in understanding the dynamic relationship between the previously introduced personality factors and the sense of presence. The trait-state distinction arises from a long-standing debate in psychology. Allport (1966) defined traits as neuropsychic structures that lead people to behave in a consistent way over time and space. They represent consistent patterns in the way one behaves, feels and thinks, which emerge through learning and are specific for individuals. On the other hand, states represent transient psychological conditions or dispositions which are dependent on the situation, manifesting themselves *here and now*.

In this context, empathy, absorption and creative imagination are enduring qualities and therefore they are traits. A person, who can be described as presenting these traits, is expected to manifest such in different situations over time, including this study. On the other hand, experiencing sense of presence is, by its inner nature, a versatile and situation dependent process. In this case, the user's sense of presence is a state, which is triggered by the experience within the virtual world.

This chapter focuses on testing the seven hypotheses, in the light of the previously outlined objectives. It presents findings regarding the impact of each personality factor on user's sense of presence. Particular attention is given to the relationship between presence–task performance which was theoretically introduced in Section 7.2.3. In this chapter, this relationship is approached in the light of personality cognitive style. The rationale of this approach is presented in Section 4.5. The description of results is followed by their discussion.

10.2 Presence and Personality Factors — A Correlational Approach

Pearson's correlations were calculated between presence scores, and scores of each of the previously mentioned personality factors. As shown in the first column of Table 10.1, with alpha set at 0.05, all the correlation coefficients were statistically significant, indicating strong positive relationships between presence and the considered variables. These findings come to validate the hypotheses stating that the more empathy (H1), absorption (H3), creative imagination (H4) and willingness to experience presence (H5) characterise and individual, the heighten sense of presence he/she will experience.

Table 10.1: Correlations Between Presence and Empathy, Absorption, Creative Imagination and Willingness to experience presence

Variable (N = 32)	Presence Questionnaire	SUS Questionnaire
Empathy	$.49^{**}$	$.46^{**}$
Absorption	$.39^{*}$	$.35^{*}$
Creative imagination	$.35^{*}$	.18
Willingness to exp. presence	$.53^{**}$	$.41^{*}$

$^{*}p < .05.$ $^{**}p < .01.$

A detailed analysis revealed that among the four dimensions captured by the empathy subscales, fantasy subscale has the strongest impact upon presence (Table 10.2). This result validates hypothesis H2.

Table 10.2: Correlations Between Presence and Empathy Subscales

Variable (N = 32)	Presence Questionnaire	SUS Questionnaire
Fantasy Subscale	$.48^{**}$	$.35^{*}$
Perspective Taking	.12	.24
Empathic Concern	$.36^{*}$	.28
Personal Distress	$.38^{*}$	$.41^{*}$

$^{*}p < .05.$ $^{**}p < .01.$

Strong positive correlations (second column of Tables 10.1 and 10.2) were also found between each of these factors and presence as measured by SUS presence questionnaire devised by Slater and Steed (2000) and introduced in Section 5.6.2.

Findings also indicate that participants more willing to be transported in the virtual world (scoring above the Median = 4) are significantly more absorbed ($t(30) = 2.74$, $p < .01$, $\eta_p^2 = .20$), more empathic ($t(30) = 2.49$, $p < .05$, $\eta_p^2 = .17$), and more imaginative ($t(30) = 2.10$, $p < .05$, $\eta_p^2 = .13$). Among all the personality factors, willingness to be transported in the virtual world correlates significantly only with the empathy score ($r(30) = .39$, $p < .05$).

10.3 Multiple Regression Analysis

Since the correlations between the considered personality factors and sense of presence are positive and statistically significant, the next step is to use these variables for predicting user's sense of presence. Multiple regression analysis, a method that can be used to study the effects of several IVs on a DV, is employed to evaluate the overall influence of previously discussed personality factors on sense of presence.

Because of the high correlation between creative imagination and absorption ($r(30) = .56$, $p < .001$), these two dimensions cannot be seen as independent predictors in the regression equation. As seen already, creative imagination and absorption are overlapping concepts, a fact indicated by their theoretical foundations and experimental studies carried out in the area of hypnosis (Crawford, 1982). Thus, a composite predictor variable as the average of these two factors was computed. Since there are no theoretical grounds for deciding the order in which the predictors should be introduced, the multiple regression was forced, with all variables entered in one step (see Table 10.3).

Table 10.3: Summary of Regression Analysis for Variables Predicting Presence

	Presence		
Variable	B	SEB	β
Fantasy Subscale	0.03	0.02	0.24
Creative Imagination & Absorption	0.09	0.04	0.29*
Willingness to exp. presence	0.19	0.08	0.37*
R^2	0.51		
Adjusted R^2	0.45		
$F(3, 28)$	9.01**		

*$p < .05$. **$p < .01$.

Results indicate that two of these factors significantly predict user's sense of presence, with willingness to experience presence making the largest individual contribution. The other significant contribution is made by the creative imagination and absorption factor. The sample multiple correlation coefficient, namely the correlation between the actual sense of presence and the predicted sense of presence was $r(30) = 0.71$, $p < .001$. About 45% of the variance of the sense of presence in the sample can be accounted for by willingness to experience presence and the creative imagination and absorption (Adjusted $R^2 = 0.45$).

10.4 Presence and Personality Cognitive Style

As shown in Table 10.4, the percentages of individuals along each dimension of personality cognitive style within the study sample are comparable to percentages found in the population (Vaccaro, 1988).

Table 10.4: Percentage of Participants Belonging to Each Bi-polar Dimension of Cognitive Style, within Sample and Population

Sample				Population			
Extrovert	73%	Introvert	27%	Extrovert	75%	Introvert	25%
Sensing	73%	Intuition	27%	Sensing	75%	Intuition	25%
Thinking	67%	Feeling	33%	Thinking	50%	Feeling	50%
Judging	50%	Perceiving	50%	Judging	50%	Perceiving	50%

Pearson's correlations were calculated between presence scores and the four dimensions of personality cognitive style. As shown in Table 10.5, significant positive correlations were found between presence and sensing and feeling dimensions. In other words, the more sensitive or feeling type an individual is, the more presence he/she will experience. Without being statistically significant, findings suggest that individuals who are more introverted may also be more inclined to experience presence. A very weak correlation was found between presence and perceiving dimension.

Table 10.5: Correlations Between Presence and Personality Cognitive Style Dimensions

Variable (N = 32)	Presence Questionnaire
Introversion	.29
Sensing	.35*
Feeling	.33*
Perceiving	.02

$^{*}p < .05$. $^{**}p < .01$.

10.5 Discussion

An analysis of the presence literature (Lombard and Ditton, 1997; Lombard, 2002; Heeter, 1992; Lauria, 1997; Slater and Usoh, 1993b), accompanied by an approach into hypnosis psychology (Tellegen and Atkinson, 1974; Barber and Wilson, 1979; Hilgard, 1979) led to the identification of the key factors of absorption, creative imagination, empathy and willingness to experience presence (see Section 4.3.2).

Results indicate that these factors play distinctive roles in the experience of presence. Significant positive correlations have been found between each of these factors and presence, indicating that the more willing to experience presence, the more empathic, the more fantasy prone, the more absorbed, or the more imaginative the users are, the greater the sense of presence they will experience.

Looking beyond the singular relationships between presence and each of its personality factors, the *presence equation* (Sas and O'Hare, 2001, 2003) is an initial attempt to predict presence based on these factors. The multiple linear regression equation 10.1 presents each variable measured as a Z score.

$$\begin{aligned} \textit{Presence} = (0.37) \cdot \textit{Willingness to experience presence} + \\ (0.29) \cdot \textit{Creative Imagination \& Absorption} \end{aligned} \tag{10.1}$$

An interesting aspect is that together, these factors cover almost half of the variance in the sense of presence. This is an important result which should encourage presence research and specifically empirical investigations of the role of individual differences in presence.

No statistically significant correlations were discovered between willingness to experience presence and the other predictors, except empathy. Results indicate, however, a statistically significant difference with respect to these predictors, between the two groups of users identified on the basis of their scores for willingness to experience presence. Thus, participants more willing to be transported in the virtual world are significantly more absorbed, more empathic and more imaginative.

It is not known if individuals feel more presence because they are more willing to, or they are more willing because of their particular configuration of personality factors. Results indicate that participants more willing to experience presence have a configuration of personality factors which predispose them to experience a higher level of presence. However, the variance in presence explained by these factors is not as high as the variance explained by willingness to experience presence factor. Willingness to experience presence and willingness to suspend disbelief are overlapping concepts and further work should be undertaken to define and understand them. The efforts invested in devising suitable tools for measuring these constructs will be justified given their high impact on presence. The independent role of willingness to experience presence and its possible determinants is a subject for future study.

Another question, which presents itself is whether willingness to experience presence is a state or a trait (Allport, 1966) (see Section 10.1). Further studies should be carried out in order to investigate this aspect. However, the attitude or mood of approaching the VR experience seems to carry a specific impact. It is more likely that the personality factors investigated in this study are latent and it is the desire to feel presence that acts as a catalyst for them. Thus, even if the willingness to experience presence might be heightened by such innate personality factors, it is nevertheless the most addressable factor in the design of the interaction with VE. It is a challenge for VEs designers to create, and encourage this desire, in order to increase the level of presence and possibly enhance users' performance (see Chapter 11).

The role of empathy and in particular of the fantasy subscale in experiencing presence has been suggested by the correlational analysis outlined in Section 10.2. However, one should be highly fantasy prone to experience a significantly higher level of sense of presence. This finding could explain the limited contribution of the fantasy subscale, which does not appear to be significant in predicting presence. The prediction model offers a hierarchy of the personality factors with respect to their impact on presence, where the role of fantasy subscale is the most limited. The lack of significance does not imply that this construct is not important in predicting presence and further studies should be conducted to clarify its contribution.

Furthermore, an interpretation of study results is presented, in the light of the hypothesis which states that different dimensions of cognitive style have an impact upon presence (H6). Breaking down this general hypothesis, the following interpretations are summarised. Along the Extroversion–Introversion dimension, the contemplative nature of intraverted individuals allow them to construct the mental model of the virtual world, providing also the energy needed to explore, understand and eventually become immersed within it (Myers and McCaulley, 1998). The level of presence experienced by intraverted individuals is significantly greater than that experienced by extraverted individuals.

In the special case of this study, where the participants worked alone, these finding seems appropriate. However, it is expected that in collaborative VEs, extraverted individuals will experience a greater level of social presence (presence of the others).

In the context of this research, the results indicate that sensing individuals experienced a greater level of sense of presence. However, this finding should be considered in relation with task characteristics. The main task of this experimental design consisted of wandering for 25 minutes within the virtual building and searching for a hidden painting. It was a highly perceptual task. Probably while learning the task, intuitive people were highly stimulated by the acquisition of a new skill (i.e. navigating), while later, the routine involved in practising it could lead to less involvement of cognitive and affective resources.

On the contrary, the more time sensing individuals spent within the environment, carrying out the same task which requires attention and precision, the more focused they became. It seems that sensing people are better anchored in the concrete, tangible reality (even when this is virtual). They easily become absorbed within the activity they get engaged with, while the remote world offers the context for here and now. Heeter (2003) posed an interesting question: “is presence for an intuitive more conceptual, while presence for a sensate is more perceptual?” The answer seems to be affirmative. In order to feel presence, intuitive individuals probably need to be stimulated with novel, symbolic information which challenges their abilities of grasping ideas.

Along the Thinking–Feeling continuum, feeling type is the empathic one. Empathy was already discussed as a quality which increases the experienced degree of presence (Sas and O’Hare, 2001). Since feeling people can potentially experience a greater level of empathy, they experience also a greater sense of presence. This result can be better understood by analysing the relationship between willingness to be transported within the remote world and the Thinking–Feeling dimension. The results indicate that feeling individuals are significantly more willing to be transported than thinking individuals ($t(28) = 2.43$, $p < .05$).

Presence-Task Performance in the Light of Personality Cognitive Style

The relationship between presence and task performance was investigated in Section 7.2.3 and findings suggested that it should be considered in the broader context of task characteristics and user gender. Section 4.3.2 argued for investigating this relationship in the light of personality cognitive style. Findings presented in Section 10.4 indicate that persons who are more sensing, more feeling or more introverted types experience a higher level of presence. On the other hand, the more extrovert, intuitive or thinking an individual is, the higher the task performance, as presented in Section 7.2.4.

The analysis of these results highlights two distinct configurations or bundles of personality traits, identified in relation to cognitive style, configurations which seem to impact differently on sense of presence and task performance.

One profile of cognitive style expressed in terms of extroversion, intuition and thinking seems to facilitate users to perform more efficiently, but has no impact on task effectiveness (i.e. collision rate). The other profile, characterising individuals more introvert, sensing and feeling type enables users to experience a higher level of sense of presence. These findings come to validate the hypothesis H7.

In the light of these findings, the apparent negative impact of presence on task performance requires careful examination. These results should be treated cautiously given the task characteristic: a highly perceptual, solitary navigational task performed within a non-immersive VE. Previously two configurations of personality traits act as predispositions, allowing users in the context of current study design to either experience presence better or to perform better.

10.6 Summary

Results indicate that at the heart of presence lie the concepts of emotion, attention and imagination. The more cognitive resources deployed, the more presence the user feels. The experience within the remote world is a complete one, encompassing cognitive, emotional and behavioural aspects. In other words, the more the users think, feel and act in the remote world and the more collateral activities are inhibited within the physical world, the greater the sense of presence they will experience.

The results enable the description of a presence equation, employing a deeper and more thorough approach to the psychology of presence. They also show that the impact of these human factors is sufficient to motivate a closer examination by both presence research community and VE designers.

Ultimately, the role of studying individual differences comes under the remit of user centred design. Once we understand the individual differences in terms of users' abilities to capture, process and make use of VR systems, the next step would be to design these VE systems to accommodate such differences (Kaber et al., 2002) (see Chapter 11). Given the potential relationship between presence and task performance, identifying appropriate VR design methods to optimise presence is crucial. Effectiveness of these designs could be increased by users' segmentation along the dimensions which derive the greatest impact on presence and performance. To what extent these human factors are addressable is discussed in Chapter 11.

Personality cognitive style is an enduring set of qualities. An individual's given traits are expected to persist over time. Cognitive style is definitely not the only extraneous variable related to subjective factors which may account for the presence–task performance relationship. Another possible variable could be any particular skill required for a specific type of task, for example spatial abilities for navigational task. In addition, cognitive style dimensions should be considered in the broader context of other personality traits, of willingness to suspend disbelief, of activity being undertaken, of media and so forth.

Whether cognitive style is part of a larger equation of a set of subjective factors which impact on both sense of presence and task performance, is a research question which deserves further investigations. Nevertheless, it can be seen as an interface which shapes our cognitive processes allowing them to be expressed in a particular, predictable way.

The different dimensions of personality cognitive styles are traits which impact upon the way we both perceive and interact with the world, either physical or virtual. The way we express ourselves (e.g. creating or designing) is the way we enjoy having things shaped, in order to experience enjoyment and ease in using them. For instance, a highly organised and structured individual (e.g. sensate) will tend to structure the content of information being processed. When the information is provided in a structured manner it will appear more appealing to the sensing type, allowing him/her to experience pleasure and to perform better. These observations are particularly of interest when applied to VEs. It is possible that a matching between the design of the VE and the manner in which individuals design things would be beneficial in terms of both sense of presence and task performance.

Madden (2001) showed that describing three-dimensional spaces in terms of personality could open up a new language in design (see Chapter 11). Her observations confirm the previously outlined conclusions and support the effort in providing guidelines for designing VE. Whether the purpose is to create VEs accommodating personality cognitive styles, than users' preferred manner of designing things could be embedded in the VE design, since it is an expression of how people like to play or interact with things. Most likely such an approach would lead to compelling VEs.

I would suggest that rather than fabricate a portfolio of instances of VEs suited to each personality trait group, to use these bundles to support dynamic Virtual World configurations to reflect the needs of each user group. Dynamic World reconfiguration has already been proposed (Guinan et al., 2000), but a model underpinning this was merely based upon blunt user profiles. The refining of user profiles with personality trait details would represent a powerful augmentation and result in higher presence and task performance.

Since the ultimate goal of studying individual differences is to enhance system usability, a major outcome of this work is to provide guidelines for designing adaptive VEs (see Chapter 11). The following chapter, the last of the Results Chapters, summarises and discusses all study findings and provides guidelines for accommodating the identified individual differences in experiencing presence and in navigational patterns. This is carried out in the light of designing more usable VEs, able to support users to experience a higher level of presence, and to adaptively support users to navigate better.

Chapter 11

Towards Accommodating Individual Differences: Design Guidelines

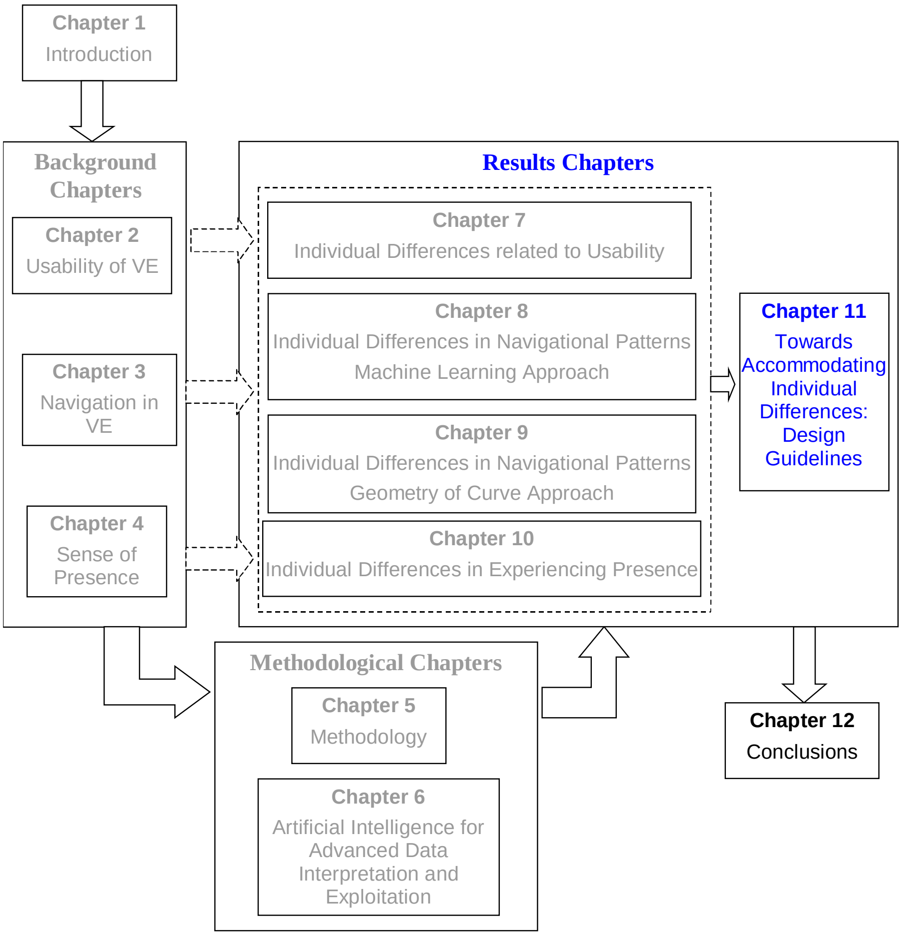

Figure 11.1: Road Map

11.1 Introduction

This chapter offers an integrative discussion of the study outcomes presented in Chapters 7, 8, 9 and 10. The discussion focuses on how the previously outlined results can be harnessed to make VEs more usable, absorbing, and navigable. It will be argued that this can be achieved through accommodating individual differences that impact on system usability, the level of presence experienced by the users, and spatial behaviour.

The design suggestions proposed in this chapter represent a main contribution of the thesis, which is to provide a new approach to the design of adaptive VEs for navigation support. At the heart of this approach lies a user model of navigation (see Section 11.4.3), expressed in terms of navigational rules and strategies. The basic idea is to help low spatial users to navigate more effectively in VEs by enabling their access to efficient spatial rules and strategies. These rules and strategies are determined by analysing the high spatial users' navigation patterns.

Sections 11.2 and 11.3 present suggestions and guidelines for the design of VEs capable of accommodating individual differences that impact upon system usability and presence. Special attention will be given to how VEs can be better designed in order to support adaptive navigation of low spatial users (see Sections 11.4 and 11.4.5). This chapter addresses the following objectives, introduced in Section 1.3:

1. The development of a set of guidelines for the design of more usable VEs,
2. The development of a set of guidelines for the design of VEs able to ensure increased presence, and
3. The development of a set of guidelines for the design of VEs able to provide navigation support to low spatial users.

It is conjectured that accommodating individual differences in experiencing presence and performing navigation improves the design of VEs which in turn leads to increased usability.

This chapter introduces a set of design guidelines for enhancing VE usability, for enhancing presence, and for supporting navigation. Given the relevance of the latter to this thesis, several issues have been further detailed. Thus, the high and low level navigational rules are summarised, and a user model of navigation is offered. Furthermore, based on these rules and this model, a generic architecture for an adaptive VE is proposed that is designed to improve low spatial users' navigation. Finally, an agent-based architecture is provided, as an adaptive version of the original non-adaptive agent-based architecture of the ECHOES system.

An observation should be made of this point. The following design suggestions are neither exhaustive nor universal. They are merely exemplifications of how the identified rules can be addressed. Within this chapter, I have simply tried to envisage a larger range of such guidelines, for exploiting the rules and suggesting their potential. However, their implementation should be a matter of design judgment, according to the purpose of the application and task characteristics, rather then being taken *ad litteram* and applied mechanically. In addition, these suggestions have been primarily conceived to be applied to VEs for individuals. This does not limit their potential to increase the usability of collaborative VEs, but in this case they require further refinement and tuning.

11.2 Design Guidelines for Enhancing Usability of VEs

As introduced in Section 2.6.3, accommodating individual differences in navigation related areas can benefit from the methodology proposed by Egan and Gomez (1985). This involves three strategies: the *challenge match*, which proposes the use of demanding tasks that force users to adapt, the *capitalisation match*, which involves properly tailored tasks designed to exploit users' potential without exceeding it, and the *compensatory match*, through which additional help is offered to address users' limitations. Furthermore, for each guideline proposed, the strategy which can accommodate the individual differences that suggested that guideline is also mentioned.

Findings indicate that the expert group performed better than the novice group, experiencing a higher level of satisfaction, limited only by the reduced control offered by the system. Therefore, in order to challenge the users familiar with computer games, the VEs should be designed to offer increased control to these users. Such an increased control can be offered through enlarging the set of actions and tasks that can be performed within the VE. Accommodating these computer experience-related individual differences requires a challenge match strategy for the male and expert groups. Designing search tasks in an environment with fewer cues and landmarks or reduced luminosity would strain these users' skills, challenging them to deploy a larger set of cognitive resources for solving the tasks. In turn, this can lead to more presence and a higher level of satisfaction with the system.

Users who experienced more presence performed the search task almost equally well if they were males, and worse if they were females.

However, this apparent negative relationship between presence and task performance for the female group, can be explained by some extraneous variables, such as increased spatial abilities for male group which leads to better performance on spatial tasks, and increased level of empathy for the female group which in turn leads to higher level of presence. In addition, females were significantly less exposed to computer games (Mean = 1.6 years) than the male group (Mean = 8.9 years), $t(30) = 4.26$, $p < 0.01$. Without being significant, females are more sensing type, while males are more intuitive type. As shown in Section 10.5, sensitive types experienced significantly higher presence than intuitive types, a fact which has been associated with task characteristics.

It can be conjectured that females perceive more thoroughly and see more details than males, a fact which supports sense of presence but impedes the formation of the overall picture (i.e. the cognitive map). No significant difference was found between experts and novices with respect to the level of presence experienced in the virtual world.

Thus, it would appear that females are better equipped to experience a higher level of presence, while males/experts can perform better the spatial tasks. Efforts should be directed to help women/novices perform better and males to experience more presence. In the first case, Section 11.4 presents some guidelines, including a system architecture (Section 11.4.5), for designing a VE able to support low spatial users to improve their navigation. It seems that the female/novice users might be the first ones to benefit from such an adaptive system, as soon as they have been identified as low spatial users. In order to help male users to experience a higher level of presence see the guidelines in Section 11.3.

It appears that individuals who experienced a high level of presence encountered a greater number of collisions. In this study, the user's set of actions was limited to navigational tasks. Thus, the only way of increasing interaction with the system involved collisions occurring during navigation. This "added interaction" with the system leads to increased sense of presence but it also leads to less accurate performances. What can be concluded is that if the system design targets both user's presence and performance, then the whole set of interactions between the system and its users should be carefully conceived to avoid interference with task performances. If both task accuracy and sense of presence are targeted, then the system should enable increased interaction, in terms of interaction modalities and range of tasks, such as manipulation and not only navigation. If only the task accuracy is to be improved, then perhaps presence can be diluted by adding, for instance sound when a collision occurs. This would be a distraction from the main task, and a warning signalising user's error. This suggestion is plausible in the context of this study where, before the experiment started, users were instructed to avoid collisions.

These outcomes suggest considerable complexity in characterising the relationship between presence and task performance, complexity which has been also investigated in the light of personality cognitive style. The analysis of results highlights two distinct configurations of personality traits, identified in relation to cognitive style, configurations which seem to impact differently on sense of presence and task performance. One profile expressed in terms of extroversion, intuition, and thinking seems to facilitate users to perform more efficiently, but has no impact on task effectiveness. The other profile, characterising individuals more as introvert, sensitive, and feeling type enables users to experience a higher level of sense of presence.

The search task is a complex one, requiring a large amount of information. However, the user has to perceive something which is beyond the immediate information, in order to build an internal representation of the spatial layout. The sensory deprivation specific to VEs (see Section 2.3.2) and in particular to desktop VEs, can put additional demands on sensing types, impeding them from building a *cognitive map* (see Section 3.2.2). This drawback can be addressed by increasing the interaction modalities (i.e. multimodal input), and by providing direct access to a map of the VE.

In addition to these proposals to ensure higher performance, each low spatial user (introvert, sensing, or feeling type) can be assisted through a VE designed according to the guidelines presented in Section 11.4. Once these users have been identified as low spatial ones through the analysis of their spatial behaviour, the VE is designed to apply a compensatory strategy to accommodate the individual differences in navigational patterns. Investigating the way in which such a strategy can be implemented represents a goal beyond the purpose of this work. Of course, a capitalisation strategy can be employed to accommodate gender related individual differences in navigation, and a challenge strategy to accommodate specific needs of expert and male groups. However, these latter strategies represent future directions and therefore are beyond of what this thesis aimed to achieve.

Findings indicate a significant effect of presence on the level of satisfaction experienced by the users. Those users experiencing higher level of presence, seem to enjoy their experience more and consequently experience a higher level of satisfaction. Additionally, users performing better are more satisfied with the system. This suggests that satisfaction in interacting with a system is a consequence of how well the system supports the tasks. To conclude, in order to increase user's satisfaction with VEs, these systems should be designed to enable users to experience presence and to be successful in accomplishing their tasks. These aspects are treated in Sections 11.3 and 11.4.

11.3 Design Guidelines for Enhancing Presence in VEs

This section summarises the results obtained in Chapter 10 where several personality factors impacting on presence were investigated. Once the individual differences which emerged as a result of this analysis have been identified, several design guidelines are proposed to accommodate them within VEs.

Results indicate that several factors play distinctive roles in the experience of presence, suggesting that the more willing to experience presence, more empathic, more fantasy prone, more absorbed, or more imaginative the users are, the greater the sense of presence they will experience (see Section 10.5). In the attempt to predict presence based on these variables, it appeared that together, some of these factors cover almost half of the variance in the sense of presence, with willingness to experience presence making the largest individual contribution. This outcome is significant and should encourage future research and specifically empirical investigations of the role of individual differences in presence. Willingness to experience presence appears to be a state which depends on the attitude or mood of those approaching the VR experience. It is likely that the personality factors investigated in Chapter 10 are latent and it is the user's desire to feel presence that acts as a catalyst for them. Thus, even if willingness to experience presence might be heightened by such innate personality factors, it is nevertheless the most addressable factor by VE designers. In order to support users' desire to experience presence, they may need special preparation before interacting with the

VE. For instance, employing a sense of drama (Laurel, 1993), a little story to stimulate their imagination could increase motivation and capture more of the user's attention (Benford et al., 2001).

With respect to the impact of the different dimensions of personality cognitive style on sense of presence, findings suggest that the sensitive, feeling, or introvert types experience a higher level of presence. These results should be treated cautiously given the task characteristic: a highly perceptual, solitary, and navigational task performed within a non-immersive VE. Given these findings, efforts should be made to support intuitive, thinking and extrovert type to experience as well a high degree of presence.

To enable intuitive types to experience greater presence, the task should be designed in a way that makes it less perceptual, which is particularly suitable for sensing type. Intuitive individuals probably need to be stimulated with novel, symbolic information which challenges their abilities to grasp abstract ideas, rather than perceiving images. This involves more challenging tasks, such as those requiring dead reckoning, particularly when intuitive subjects are high spatial users. More abstract, strategic tasks consisting of manipulating symbolic data could help intuitive users to experience more presence.

Thinking types can be helped to experience greater presence through manipulating the media content, in terms of the entire scenario aimed at preparing the subject for the VR experience and increasing the willingness to be transported in the virtual world. Extrovert types can be helped to experience a higher level of presence, by enabling them to perform collaborative tasks within the VEs. In addition, this can lead to an increased level of social presence (presence of others).

The fact that the *objective happenings* (Jung, 1971) carry immense fascination for the extraverted type, until one ultimately loses oneself in them, is worth mentioning (see Section 4.3.2). Study findings suggest that absorption is a cognitive factor which impacts on presence, and therefore the challenge is how to design properly the objective happenings. It is likely that a range of possible interaction modes, a large variety of tasks including collaborative ones and/or elaborated scenarios could enhance the extroverts' sense of presence. In this light, CVEs (see Section 2.3.1) appear to be a promising venue for enabling extraverted types to experience both presence and co-presence.

Regardless of whether the goal of a VE is to induce presence or to enable users to perform better, account should be taken of the various personality trait combinations. For example a VE for games should be particularly designed to allow extrovert, intuitive and thinking type individuals not only to perform better in spatial tasks but to experience presence as well.

When, for instance, the VE is designed for medical applications (Sas et al., 2001), its main purpose is to enable surgeons to perform at least as well as they would perform in reality (with or without presence). In this case, particular attention should be given to introvert, sensitive and feeling types who experience a higher level of sense of presence but whose performance might be reduced. The enhanced realism or multi-modal inputs could be solutions in this direction.

11.4 Design Guidelines for Navigation Support within VEs

This section proposes a set of design guidelines based on the findings of this thesis (see Sections 8 and 9). Such guidelines should be seen in the larger frame of the guidelines reviewed in Section 3.3.4, and whose major limitation they address. This limitation is related to the emphasis on technological aspects of VEs. These technological aspects, including different navigation tools, are manipulated or employed with little or no attention to human factors.

Studies focusing on building VEs according to those design principles and guidelines summarised in Section 3.3.4 present an additional limitation. They do not explain how these different techniques and tools can be related to the user's mental model of navigation. Thus, such techniques have been applied indiscriminately to all the users. There is, therefore, a need for another approach to the design of VEs for navigation assistance.

Without underestimating the role of the design guidelines summarised in Section 3.3.4, this thesis argues that before focusing on navigational cues and tools, it is necessary to understand how these tools can be differently employed and tuned for various groups of users, in order to serve their specific needs.

This section proposes designing VEs in a way that enables them to access the user model of navigation and to accommodate themselves accordingly. Such *adaptive* VEs (see Section 2.6.2) present the considerable advantage of being able to adapt to users' individual differences.

Given the complexity of and difficulties in capturing navigational rules, an inherent part of users' spatial mental models (see Sections 3.2.2 and 3.2.4), several methods of analysing and interpreting data have been employed (see Section 5.9). Such a methodological and theoretical triangulation (see Section 5.5.1) enabled the identification of a larger set of rules which could not have been captured by the employment of just one method. Sections 11.4.1 and 11.4.2 concisely present these rules.

11.4.1 High-Level Navigational Rules

The first method employed for capturing rules consisted of a set of machine learning techniques described in Chapter 6. These techniques proved particularly useful in capturing some high level rules or navigational strategies. The findings presented in Chapter 8 suggest two efficient strategic rules which are summarised below.

The first rule identifies specific areas, called *surveying zones.* Such zones are particularly appealing to high spatial users, but not to low spatial ones. What is interesting is that the attraction of these areas is not explained by the presence of some relevant landmarks, but quite contrarily, these zones are landmark free. Their attractiveness consists of their openness, which enables users to acquire a significantly larger view of their surroundings. Such observational behaviour provides users with valuable information about spatial layout and landmark configuration.

The second rule presents an efficient way in which high spatial users conserve their resources. Moving in an indoor, unfamiliar VE which is cluttered with objects requires users to be selective and able to prioritise their visits to particular landmarks. This rule regards the movement pattern while none of the surrounding objects presents any interest for the user. In this case, the user moves along an *equilibrium path*, thus maintaining almost equal distance to each of the landmarks in his immediate vicinity. When one of the landmarks raises user's interest so that he/she decides to give it a closer look, this median path is not followed anymore and the user gravitates towards this particular landmark, with minimum energy expenditure.

The machine learning approach led also to the identification of one inefficient strategic rule. This rule is related to the difficulties encountered by low spatial users in passing through the sliding doors which separate each two adjacent rooms within the ECHOES VE. As mentioned in Section 8.5.7, such door design puts unusual demands on users. These doors are designed to briefly open only when users are in their proximity, facing them almost at a right angle. This finding is particularly relevant to the present discussion, suggesting how an inappropriate design can impede the performance on spatial tasks of low spatial users. Section 11.4.4 presents some design guidelines to address this limitation.

11.4.2 Low-Level Navigational Rules

The previous method for rule extraction has been complemented by one inspired by a geometry of curves, detailed in Section 9. Section 9.5 presents the results of employing Bézier curve fitting and some statistical analysis. These results reflect low level spatial rules, summarised in Table 11.1.

The rule summary in Table 11.1 offers an additional benefit. By presenting both efficient and inefficient navigational rules, it provides a means to identify and understand inefficient spatial behaviour of low spatial users. More importantly, apart from the diagnostic potential, this summary also offers the key for addressing the limitations characterising the behaviour of low spatial users. The adaptivity problem can be formulated in terms of how spatial behaviour of low spatial users can be influenced in order to help them to overcome their inefficient navigational rules and learn the efficient ones.

The previously summarised rules and strategies represent insights into users' spatial mental model, from where they have emerged and have been captured. The following section introduces the user model of navigation, elaborated based on these findings.

Table 11.1: Low Level Navigational Rules

Efficient Rules	**Inefficient Rules**
Rotations	
Low absolute curvature	High absolute curvature
More small rotations	Fewer small rotations
Fewer great rotations	More great rotations (sharp angles)
Fewer changes of heading (> 90°)	More changes of heading (> 90°)
More rotations on average per trajectory (12)	Fewer rotations on average per trajectory (10)
Fewer successive rotations in average per trajectory (2)	More successive rotations in average per trajectory (3)
Observational angle	
Small changes of heading (< 45°)	High changes of heading (> 65°)
Moving angle	
Small changes of heading (< 35°)	High changes of heading (> 50°)
Translations	
More translations in average per trajectory (12)	Fewer translations in average per trajectory (10)
Fewer successive translations in average per trajectory (1.6)	More successive translations in average per trajectory (1.8)
Shorter segments covered by consecutive translations (3 virtual metres)	Longer segments covered by consecutive translations (4 virtual metres)
Smooth trajectory	Trajectory with zigzags
Greater area enclosed by the trajectory	Smaller area enclosed by the trajectory
Behaviour around landmarks	
More rooms visited (9)	Fewer rooms visited (7)
More landmarks visited (16)	Fewer landmarks visited (11)
More movements near landmarks of interest (20 events)	Fewer movements near landmarks of interest (14 events)
Closer moves to the landmarks of interest (1.5 virtual metres)	Farther moves from the landmarks of interest (2 virtual metres)

11.4.3 User Model of Navigation

The distinction between *user spatial mental model* and *user model of navigation* has been often drawn in HCI literature (Fischer, 2001; Norman, 1983; Preece, 1993; Benyon and Murray, 1993) and referred to in Sections 2.6.2 and 3.2.1. The user mental model is developed by users during their interaction with the system, while a user model consists of knowledge that the system holds about user's mental model in order to improve the interaction (Finin, 1989). The only way a system can adapt itself to successfully accommodate different groups of users is through the embodiment of the user model, a simplified schema of the more complex user mental model. Based on the previously identified navigational rules and strategies, a user model of navigation has been elaborated. Figure 11.2 depicts this model, where white arrows represent the flow of actions, and the black arrow represents a loop. The shadowed boxes present rules governing the behaviour outlined in the nearby boxes. Only efficient rules have been considered in the development of this model, since this model (and not the inefficient one) serves as a basis for adaptivity.

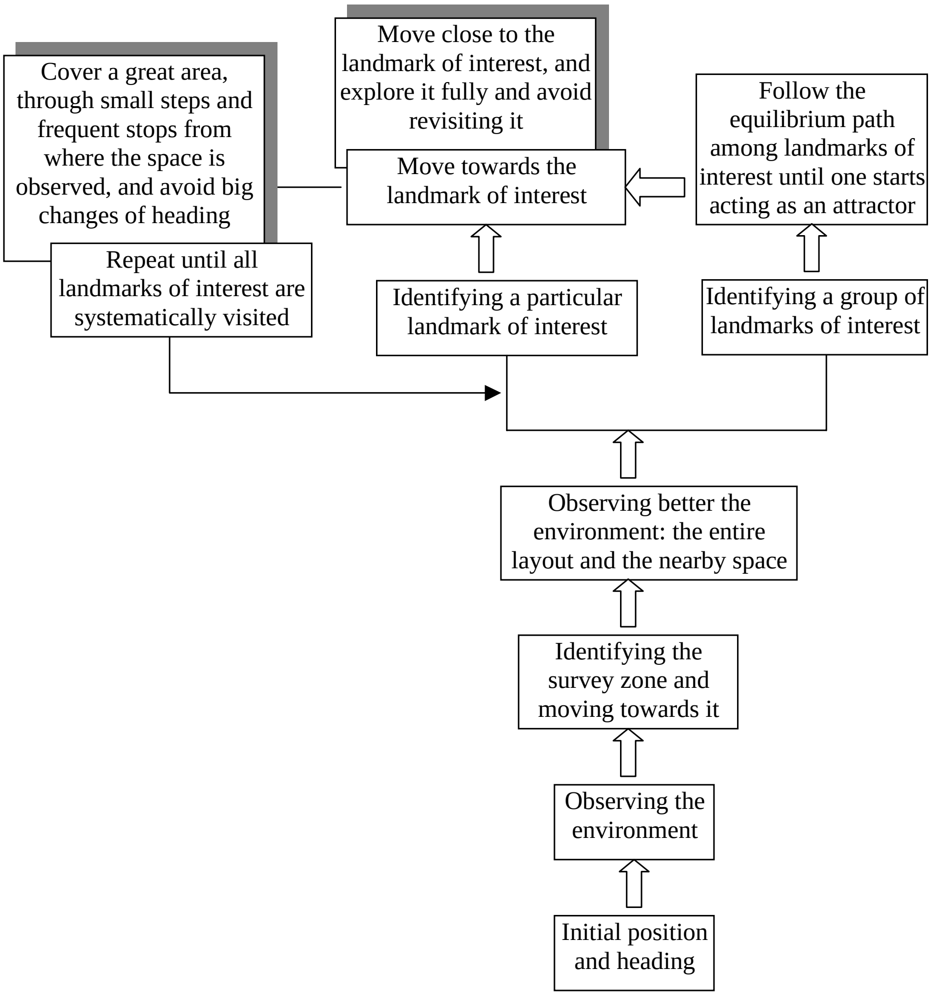

Figure 11.2: User Model of Navigation

From the original location where the user is automatically placed by the system, the user starts observing the environment through changing his/her heading. Besides acquiring valuable information about the spatial layout, such observations allow the user to identify the *surveying zone*, from where a better observation is enabled. Through performing a thorough observation while located in such surveying zone, user can identify a particular landmark of interest, or a group of landmarks sharing spatial proximity. In the first case, the user moves towards the landmark of interest and observes it closely, according to the efficient rules governing the behaviour around the landmarks. This decreases the need for later revisits. When the user is attracted by a group of landmarks, he/she follows the *equilibrium path* among them, until a landmark becomes a stronger attractor. At this moment, the median path is not followed anymore, and the user moves with minimum energy expenditure towards that particular landmark. Such a landmark is efficiently observed as described above. Once a landmark is explored like this, the user continues with the next landmarks of interests, in a systematic order. In this recursive process, the user tries to cover the greatest possible area, given his limited resources. Along his/her route, a high spatial user carries out small steps and frequent stops which enable him to observe the space from numerous locations, while avoiding great changes of heading.

11.4.4 Design Guidelines

This section presents some design guidelines to address the navigational rules summarised in Sections 11.4.1 and 11.4.2. These design guidelines, related to navigational rules and strategies, can be implemented at the level of VE, at user level, or at both levels. This implies reconfiguring the VE, or modifying the interaction with VE. Both strategies aim to determine low spatial users to change their inefficient navigational patterns into more efficient ones.

Addressing and accommodating individual differences according to the design guidelines outlined below is an intrinsic part of *instructional design*, defined by Berger (2003) as follows:

> Instructional design is the systematic development of instructional specifications using learning and instructional theory to ensure the quality of instruction. It is the entire process of analysis of learning needs and goals and the development of a delivery system to meet those needs. It includes development of instructional materials and activities; and tryout and evaluation of all instruction and learner activities.

Instructional strategies determine the approach taken for achieving the learning objectives, which should be appropriate with users' expertise, skills, learning interest and learning style (Education, 1991). Choosing between an instructional strategy which would facilitate explicit or implicit learning represents another decision related to instructional design. *Explicit learning* is an active process which occurs mainly consciously and involves learner's deliberate efforts to structure the information through elaborating and testing different hypotheses in the search for that structure (Ellis, 1994). *Implicit learning* is a passive process which occurs without conscious operations, through simple exposure of the learner to information, and without any effort. It is "the acquisition of knowledge which takes place largely independently of conscious attempts to learn largely in the absence of explicit knowledge about what was acquired" (Reber, 1993).

Since usually the knowledge behind the spatial skills is implicit, a suitable way to address them might be an implicit one. This does not exclude the explicit ways of implementing corrections, particularly if they match user's learning style (Ford, 2000; Pask, 1988). Some guidelines further proposed may need to be indirectly implemented to enable implicit learning, while others, given the relevance of the particular aspects they try to convey, might require a more direct approach which can facilitate explicit learning.

Alternatively, each particular rule can be gradually taught to the low spatial users, on a continuum starting with instructional strategy which enables implicit learning, and ending with those enabling explicit learning. Passing along this continuum from one way of implementing rules to another, is related to the learner's flexibility in assimilating the rules. An expression of the learning success consists of changes in user's spatial behaviour, changes which are expected to occur and recorded in real time.

The guidelines described below require instruction strategies which facilitate both implicit and explicit learning, and both indirect and direct approaches. The level of intrusion in correcting inefficient spatial behaviour could be seen as impacting on the lasting effects of corrections. This work particularly argues for a more subtle, implicit and liberal way to teach the efficient ways to navigate. Such a teaching manner is expected to challenge user's navigational model, rather than correcting their immediate behaviour. Without being yet validated empirically, such an approach has considerable face validity. This section starts by addressing the high level rules, and continues with low level rules.

Design Guidelines for High Level Navigational Rules

The individual differences in navigation related to the first efficient navigational strategy can be accommodated by placing a particular type of landmark in the middle of the *surveying zone* (see Section 11.4.1). Such a landmark should be intuitive enough to enable low spatial users to perform rotations around it while facing the virtual world, rather than facing the landmark. Such a landmark can take the shape of a column or pillar, which is not interesting in itself, but can suggest being used as an observation point. Moving around such a landmark, users can get a larger view field of the environment. Alternatively, low spatial users can be transported near this landmark, and rotated around its axis, in a carry away mode.

According to the second efficient strategy, keeping the users on the *median path* among the nearby landmarks seems to be an expected target trajectory. One way to correct the deviant trajectories could consist of a smooth relocation of the nearby landmarks, such that the equilibrium path is preserved.

The limitation relating to inefficient navigational strategies can be simply addressed by a different design of the sliding doors within the VE. One way is to make these doors more flexible in terms of enabling them to open and remain open when users are in their vicinity, irrespective of the angle at which they face the doors. Other possible solutions to be tested in the future consist of removing the door completely and keeping only their frames, allowing users to pass through the doors, or replacing them with door curtains.

Design Guidelines for Low Level Navigational Rules

The low level rules summarised in Section 11.4.2 are addressed in terms of design guidelines. These guidelines are organised consistently with the headings of low level rules from Table 11.1: translational behaviour, rotational behaviour and behaviour around landmarks (Sas et al., 2004a). Some of these guidelines are used to design the architecture of an adaptive ECHOES VE (Section 11.4.5).

Rotational behaviour. This section presents the guidelines for designing an adaptive VE which focuses only on some navigational rules related to rotational behaviour. Such rules were chosen because of their prevalence: almost 50% of the identified rules are related to rotational behaviour (Section 11.4.2). In addition, how much and how often users rotate, and why they choose a particular heading for the following translation are aspects of relevance for spatial performance. Consequently, accommodating individual differences related to rotational behaviour could significantly impact on users' performance and perceived system usability. The design proposed for building an adaptive version of ECHOES system addresses the following rules:

1. Efficient navigators perform fewer changes of heading smaller than 90°, compared with inefficient navigators.
2. Efficient navigators perform more rotations on average per trajectory (12) than inefficient navigators (10).
3. Efficient navigators perform fewer successive rotations on average per trajectory (2) than inefficient navigators (3).

These rules can be implemented through the following design guidelines.

- A subtle instruction strategy regards the real time modification of VE, in terms of reducing the default rotational step, associated with each press of the left arrow or right arrow key. In this case, a similar change of heading will require more keystrokes, which might increase user's awareness of his rotational behaviour. This can potentially lead to further self-readjustments which can determine a more efficient rotational behaviour.
- An explicit instruction is through a message which explicitly warns the user that the degree of rotation which has just been performed is too large and the user is at risk of disorientation.
- A conservative correction consists in disabling user's translation after a change of heading greater than 90°. In other words, users are enabled to rotate, but disabled to move after a large change of heading took place. They can continue to rotate and the translations are enabled if user's current heading does not differ by more than ±90° from the user's heading of the previous translation.

Translational behaviour. This section presents the guidelines for designing an adaptive VE which focuses only on some navigational rules related to translational behaviour:

1. Efficient navigators perform more translations on average per trajectory (12) than inefficient navigators (10).

2. Efficient navigators perform fewer successive translations on average per trajectory (1.6) than inefficient navigators (1.8).
3. Efficient navigators cover shorter segments within successive translations (3) than inefficient navigators (4).

These rules can be implemented through the following design guidelines.

- An implicit correction regards the dynamic modification of VE, in terms of reducing the default translational step, associated with each press of the up arrow or down arrow key. In this case, a similar length of segment will require more keystrokes, which might increase user's awareness of his translational behaviour.
- An explicit instruction is through a message which explicitly warns the user that the length of the segment which has just been covered is larger than necessary and it will be more efficient to stop and observe the environment (i.e. rotate).
- A conservative correction consists in disabling user's translation after a segment greater than 3 virtual metres has been covered. Thus, users are explicitly prevented from moving, so that they can only rotate. After the heading is changed, the user is allowed to perform both rotations and translations.

Behaviour around landmarks. This section presents the guidelines for designing an adaptive VE which focuses on some navigational rules related to behaviour around landmarks:

1. Efficient navigators visit more rooms (9) than inefficient navigators (7).
2. Efficient navigators visit more landmarks (16) than inefficient navigators (11).
3. Efficient navigators perform more movements near the landmarks of interest (20) than inefficient navigators (14).
4. Efficient navigators move closer to the landmarks of interest (1.5) than inefficient navigators (2).

Before presenting the design guidelines for implementing the rules related to user's efficient behaviour around landmarks, two working definitions should be introduced. The landmark closest to the user's current position is called an *attractor*, and the vicinity of an attractor is called the *attractor basin.* This is an area which contains all the points located at a distance shorter than 1.5 virtual metres from the attractor.

The design guidelines for implementing the rules regarding the spatial behaviour around the landmarks, are described below.

- An implicit correction involves placing the user into an unvisited room, if having visited fewer than 7 rooms, the user is trying to revisit some of them. In this way, revisiting is allowed only after at least 9 different rooms (75% of the total number) have been visited.

- Reorienting, or changing a user's heading towards an unvisited landmark, if after visiting 11 landmarks the user is trying to revisit them. This implies that the user is encouraged to search around new landmarks, and only after he/she moved closer to at least 16 different landmarks, he/she may revisit them.
- Placing the user near an unvisited landmark, if he/she is trying to revisit any of 11 (or fewer) visited landmarks.
- If the user faces the nearest landmark and moves in its attractor basin at a distance greater than 2 virtual meters, then the VE is reconfigured by placing the landmark closer to the user.
- If the user tries to leave the attractor basin of the nearest landmark after performing fewer then 14 translations or rotations, then the user is maintained in the basin. One way to enable this is by not allowing translations which would let the user to withdraw from the basin, and by reorienting user's heading towards the attractor.
- A direct method to implement these rules is through a pop-up message which explicitly warns the user that there are still rooms or landmarks to be visited, or that the search around the landmark is not thorough enough.

A final observation should be made at this point. The dichotomy between high and low level spatial rules based primarily on the rule extraction methodology is not exhaustive and therefore it needs to be refined. It appears, particularly during the elaboration of the above guidelines, that some rules cannot be directly implemented. This led to the identification of three medium level rules, summarised in Table 11.2. Implementing, for instance, the efficient rules referring to smooth trajectory paths and greater enclosed areas would emerge through implementing rotational and translational behaviour-related rules. Similarly, the efficient rule of revisiting fewer landmarks is based on the implementation of other rules related to behaviour around landmarks.

Table 11.2: Medium Level Navigational Rules

Efficient Rules	**Inefficient Rules**
Smooth trajectory	Trajectory with zigzags
Greater area enclosed by the trajectory	Smaller area enclosed by the trajectory
Fewer landmarks revisited (4)	More landmarks revisited (7)

As mentioned in Section 3, these rules and strategies have a twofold purpose. On the one hand, they offer a deeper understanding of how high spatial users navigate in an unfamiliar indoor VE, thus offering an insight into their mental spatial model. On the other hand, such rules are merely simplifications which do not capture the full richness characterising user's spatial behaviour. However, they identify some relevant features which have the considerable advantage of being fully articulated, and therefore able to be used in the system design (see Section 11.4.5). This is important, particularly when the design of VE aims to assist low spatial users in their spatial tasks. The identified rules represent different aspects of user's spatial mental model and lie at the core of the architecture of the adaptive ECHOES VE, described in the following section.

11.4.5 Adaptive ECHOES

Designing adaptive VEs able to support navigation of low spatial users can now benefit from the above navigational rules and strategies. The particular purpose of supporting low spatial users' navigation requires a *compensatory* accommodation strategy (see Section 11.2). The effective navigational rules summarised in Table 11.1 can be used to limit the negative impact on spatial performance of low spatial users who repeatedly apply inefficient navigational rules. Ways to accommodate such inefficient behaviours and accordingly to address the individual differences which stay behind the inefficient rules are only limited by the designer's imagination.

Adaptive ECHOES Architecture

The proposed architecture for an adaptive VE is based on the schema presented in Figure 11.3, where ovals represent input or output, rectangles represent processing methods and grey box figure represents stored information. This general schema of ECHOES adaptive system is based on the general schema developed by Jameson (2003) (see Section 2.6.1).

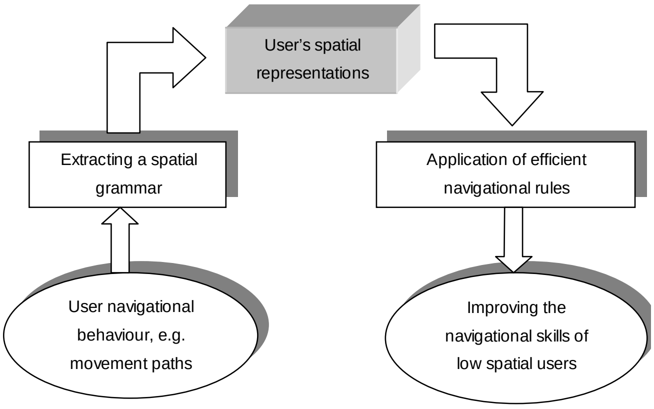

Figure 11.3: Schema of the Adaptive ECHOES

Before the system can start adapting itself to assist low spatial users, it has first to be able to identify those low spatial users. Section 8.2 presents in detail both the method and results related to clustering trajectories. This led to five clusters, obtained by applying Self-Organising Maps on the trajectories followed by the participants in this study. Among these clusters, of particular interest is Cluster 2. It is argued that this cluster groups poor trajectories covered particularly by low spatial users.

Previously identified features, under the heading of inefficient rules and strategies (Table 11.1) specifically characterise the poor trajectories. The fact that there is a significant difference between the number of poor trajectories (66%) and the number of good trajectories (33%), ($\chi^2(1) = 16.34$, $p < 0.05$) within Cluster 2 suggests that trajectories composing this cluster are predominantly poor trajectories. This is an outstanding result which links users' patterns of spatial behaviour, their spatial performance, and the possibility of identifying online and unobtrusively this group of low spatial users. For a detailed presentation of the method employed for clustering trajectories which led to five clusters, including Cluster 2, see Section 8.2.

The entire process of designing the adaptive ECHOES can be broken down into two main phases. The first phase puts forward the work carried out in Chapters 8 and 9, and Section 11.4.3. An overview of how this work fits into the larger picture of designing adaptive VE is depicted in Figure 11.4.

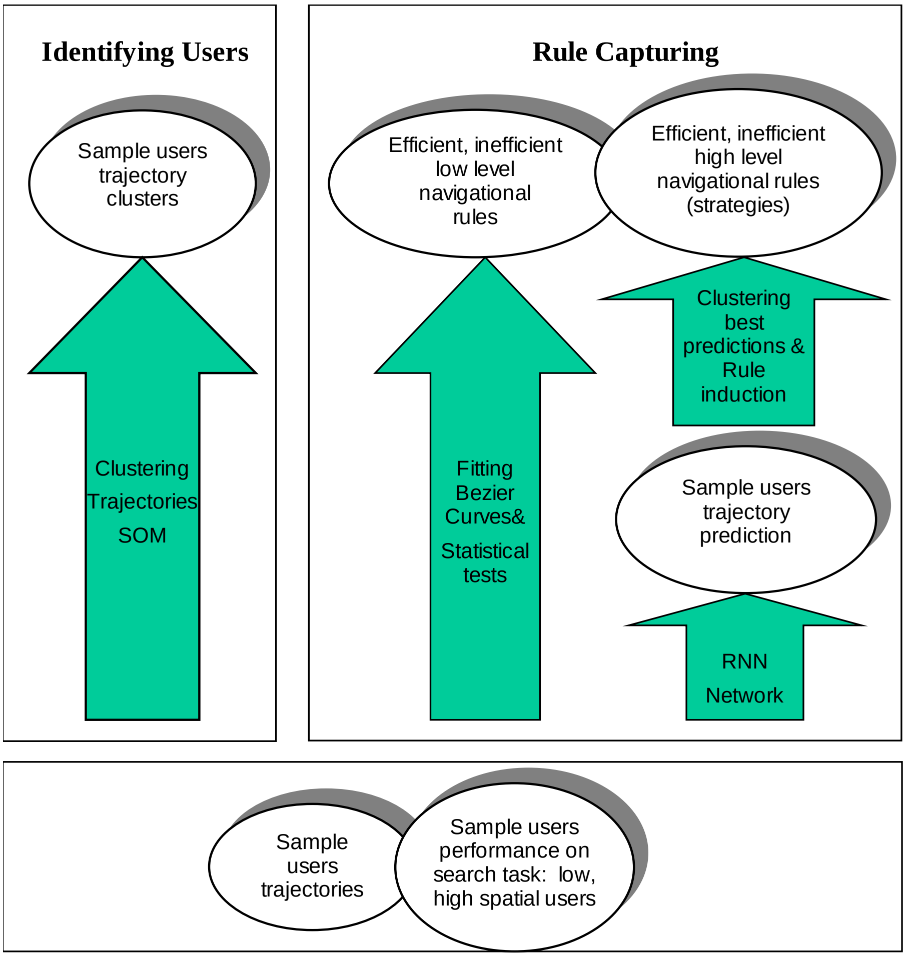

Figure 11.4: Phase 1. Building an Adaptive VE Architecture: Identifying User Class and Rule Capturing

The first phase consists of two overlapping stages. The first stage proposes a diagnosis tool to differentiate efficient navigators from inefficient ones, or in other words to identify users according to their spatial behaviour patterns as high or low spatial users.

This stage involves the use of Self-Organising Map (SOM) which has been trained to cluster users' trajectories (see Section 8.2). Based on search task performance, the obtained clusters were identified as reflecting and consequently discriminating efficient from inefficient trajectory patterns.

The second stage of the first phase aims to extract rules and strategies governing users' spatial behaviour, through machine learning and geometry of curves approaches. Extracting knowledge from the trained Recurrent Neural Network (RNN), which learned to predict users' trajectories, allows the exploration of regularities, implicitly embedded into the trajectory paths (Chapter 3). Low level navigational rules have been obtained through fitting Bézier curves to users' trajectories and employing a set of statistical tests between different features identified within efficient vs. inefficient users' trajectories (see Chapter 9).

An important observation should be made at this point. The results presented in Chapters 8 and 9 have been obtained through a thorough investigation of a sample of 32 participants. The spatial behaviour of these subjects was recorded and their analysis allowed the identification of some navigational rules. This constitutes a prerequisite for the design of any adaptive system. However, using the findings obtained on the basis of study sample, in order to assist the navigation of each *new* low spatial user (not belonging to the study sample) is the challenge that the system has to face.

The second phase of developing the adaptive VE architecture involves applying the information encapsulated in the user model (see Section 11.4.3) to support the spatial behaviour of each new user (see Figure 11.5).

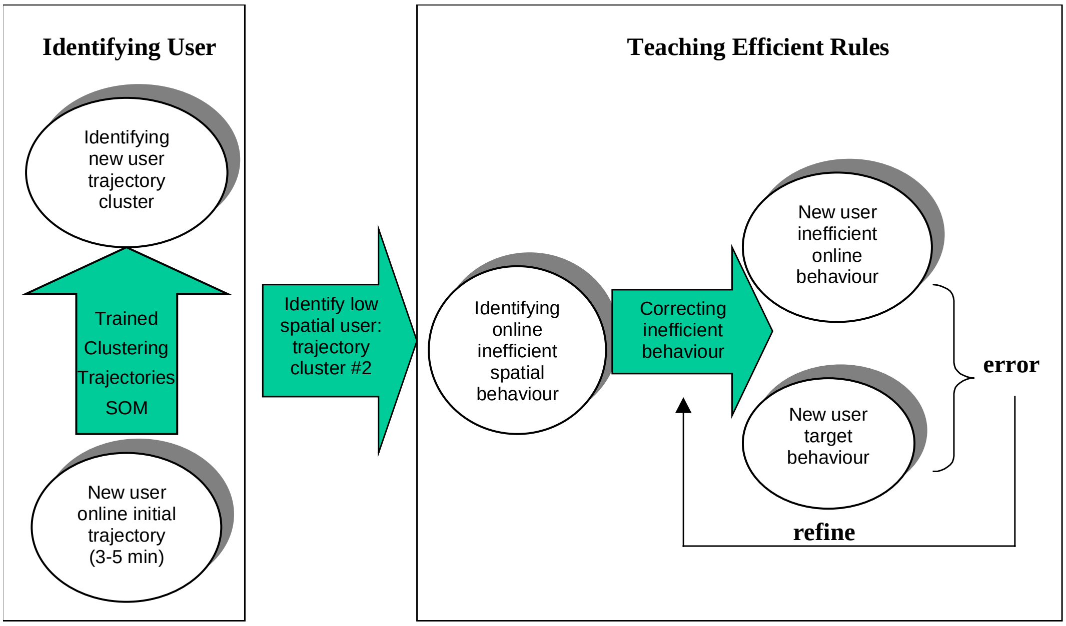

Figure 11.5: Phase 2. Building an Adaptive VE Architecture: Applying the Efficient Navigational Rules for Supporting Low Spatial Users

After the user is left to navigate for about 3–5 minutes, while he/she usually covers the ground floor of the virtual building, his/her stored trajectory is assigned to the appropriate trajectory cluster. The already trained SOM is able to perform on-line trajectory classification. Section 8.2 described how these clusters were identified using the set of trajectories performed by the study participants. Apart from being identified, the clusters were tested and the accuracy of classification has been computed. The open source of SOM_pak and LVQ_pak packages used for obtaining these results allows these programs to be made an intrinsic part of the adaptive ECHOES architecture. Thus, the trajectories of each new user are assigned to one of the identified classes with a certain accuracy.

When a trajectory is assigned to Cluster 2 (see Section 8.2) it means that it can be described by those features captured by the inefficient navigational rules and strategies. Thus, the user following that trajectory is identified as being a low spatial user who needs navigation assistance. The architecture of the adaptive VE system described below is designed to accommodate only those users whose trajectories are assigned to Cluster 2.

A major contribution of this thesis consists of identifying some navigational rules, and proposing possible ways of accommodating them through the design guidelines outlined above. The next logical step involves the implementation of these guidelines, which is beyond the purpose of this thesis. Implementing the guidelines requires a large amount of work, given not only their diversity, but also the manner in which these guidelines interact and influence each other. Several usability tests should be conducted, with different versions of adaptive ECHOES, against non-adaptive ECHOES, in order to identify which guidelines, combination of guidelines or instructional strategies prove more efficient in supporting low spatial users' navigation. Various aspects of instructional design (Berger and Kam, 2003) should be taken into consideration while implementing these guidelines.

In an attempt to fill the gap between the presented findings and this future direction, the thesis makes a step further by also presenting the agent-based architecture of the adaptive ECHOES, able to implement some of the design guidelines which have been elaborated. As mentioned above, implementing and testing all the identified rules and guidelines is beyond the purpose of this thesis.

11.4.6 Agent-based Adaptive ECHOES Architecture

The adaptive version of ECHOES system is supported by an agent-based architecture. The motivation for this choice is twofold. Firstly, the non-adaptive version of ECHOES has been developed through an agent-based architecture. Therefore, it is important to develop and refine this agent-based architecture for designing the adaptive version of the ECHOES system. The second reason is related to the entire set of features which define agents and make them suitable candidates for this purpose. One main argument in this sense is the inherent complexity of any VE system which should be able to handle in real time the changes of both the environment and users' movements. A multi-agent system which enables control and communication among its agents is a perfect way to accommodate the dynamics related to an adaptive VE (Sas et al., 2004b).

The provision of agent-based navigation support within VEs is not new, given particularly the recent work in the design of intelligent support for navigation in VEs (Dijk et al., 2003; Volbracht and Domik, 2000; Nijholt et al., 2001). Such work is usually limited to encoding some general navigation heuristics, and without identifying the groups of users who require special assistance.

Before presenting the agent-based adaptive architecture, an overview of non-adaptive ECHOES architecture is required. Figure 11.6 presents a high level view of the agent-based ECHOES architecture as described by O'Hare et al. (2000b; 2000a) and Delahunty (2001), where arrows represent the flow of data from the user through the agents and database where it is stored and eventually reused.

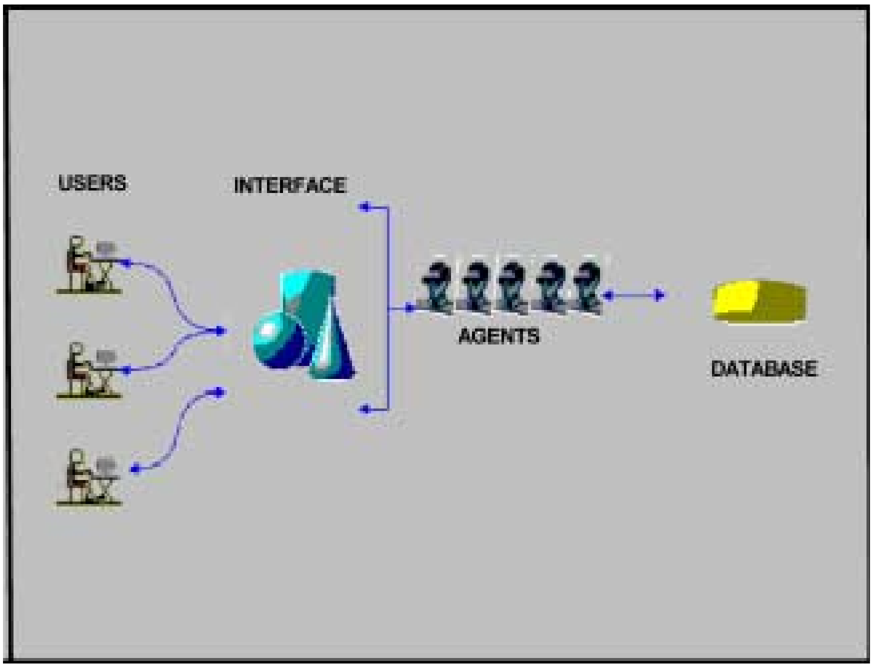

Figure 11.6: ECHOES: Architecture Overview

The ECHOES architecture involves five agents, among which only the Listener Agent is relevant to the topic of this thesis. The Listener Agent records data about user behaviour within the VE in terms of navigation paths through the world and time spent in different rooms. The ECHOES agents were built via Agent Factory, a rapid prototyping environment for agent design and delivery (O'Hare and Abbas, 1995; Collier et al., 2003) (see Section 6.5.1). Central to these agents is a rich mental state comprising an aggregation of a set of beliefs, a set of commitments to future directed actions and a set of commitment rules that drive the adoption of commitments.

Figure 11.7 presents a high level view of the adaptive agent-based ECHOES architecture. The proposed agent-based adaptive architecture of ECHOES system involves four agents: Listener Agent, which has been already developed, Classification Agent, High Level Adaptivity Agent and Low Level Adaptivity Agent. Each of these agents will be further described.

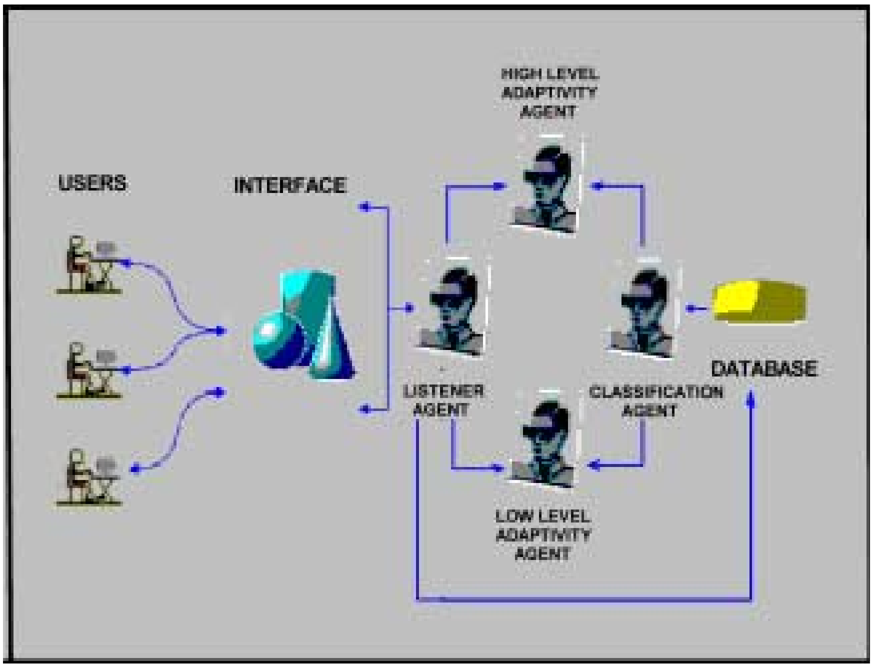

Figure 11.7: Adaptive ECHOES: Architecture Overview

Listener Agent records and stores in the database all the information about users' behaviour within the VE. The occurrences of navigational events (translation or rotation) are logged by the Listener Agent in the database and communicated to each of the other agents.

Classification Agent is responsible for performing user classification. This agent is based on *clustering trajectories* which represents a modular system which has been presented in detail in Section 8.2. This Classification Agent takes as input the data recorded in real time by the Listener Agent and stored in the database. Buffering data in this way is necessary because the *trajectory classification* module works with complete trajectories, (e.g. on the ground floor).

Identifying the quality of users' spatial abilities through the analysis of their spatial behaviour is another benefit provided by this Agent. This is possible because previous work focused on linking users' trajectories with their performance on spatial tasks (e.g. search task). This led to a qualitative interpretation of trajectory clusters: for instance, Cluster 2 groups mainly the trajectories performed by users with worst performance on the search tasks, or by low spatial ones.

It is remarkable that the data used to train and subsequently to test Self-Organising Map (SOM) (see Section 8.2) are unobtrusively collected by the Listener Agent. These data consist of naturally occurred behaviour, such as users' movement paths within the VE. Therefore, Classification Agent offers the advantage of not requiring users to undergo any spatial abilities tests before the beginning of their VE experience. This agent provides as output the class to which the user belongs, based on the movement paths. The output of Classification Agent is communicated to Adaptivity Agents.

High Level Adaptivity Agent is responsible for implementing the design guidelines related to high level navigational rules (see Section 11.4.4). This agent is particularly focused on changing some aspects within the VE, in order to assist low spatial users to navigate better.

Low Level Adaptivity Agent is responsible for implementing the design guidelines related to low level navigational rules (see Section 11.4.4). This agent is particularly focused on helping the user to change some aspects in his/her spatial behaviour.

For exemplification, the mental state of Low Level Adaptivity Agent at a given moment in time is depicted in Figure 11.8. The mental state of an agent continually evolves with respect to time, as the agent perceives new environmental events and deduces new observations about the user behaviour. Each will result in belief update and the addition and/or dropping of beliefs. In turn, the beliefs drive commitment rule activation and in turn commitment adoption and ultimately the activation of actions that assist in user navigation.

The Figure 11.8 presents a set of commitment rules belonging to Low Level Adaptivity Agent. The first commitment rule states that if the user classification is unknown then the agent ought to commit to performing a classification. This results in a request to Classification Agent, which will when be able to return the classification via communication. Inter-agent communication takes the form of speech acts and the Low Level Adaptivity Agent will receive a speech act as to the user category. An agent preceptor would recognise this communication and accordingly adopt a belief the current user was the category communicated by the Classification Agent.

The second and third commitment rules concern navigational interventions, which the agent is empowered to perform. In the case of the former, if the user is of low spatial ability category and there are more than 3 successive rotations which induce an overall changing of heading greater than 90°, then the system would implicitly degrade the responsiveness of the rotation step thereby assisting the user in exploration. This is a case in point where the user may remain unaware of the agent intervention. In some cases, this unobtrusive instruction strategy may not lead to the expected changes in user's spatial behaviour, such that he/she continues to perform changes of heading greater that 90°, during more than 10 rotational events. If this is the case, commitment rule 3 alerts the user with a warning such as: "Be careful! You rotate too much and may become disoriented". This commitment rule directly and explicitly tries to convey the efficient rotational rule to low spatial users. However, it is activated only if the unobtrusive commitment rule failed to reach its goal.

```
BELIEF (User_Classification (UNKNOWN))
        => COMMIT(Self, Now, Classify_User() )

BELIEF (User_Classification (Low_Spatial)) &&
BELIEF (Rotation_number (>3)) &&
BELIEF (Rotation_angle (>90))
        => COMMIT (Self, Now, reduceRotationStep(50%))

BELIEF (User_Classification (Low_Spatial)) &&
BELIEF (Rotation_number (>3)) &&
BELIEF (Rotation_angle (>90)) &&
BELIEF (Rotation_events(>10)
        => COMMIT (Self, Now, Warning_DisorientationRisk())
```

Figure 11.8: Mental State of Low Level Adaptivity Agent

11.5 Summary

This chapter summarised the study findings with the purpose of providing guidelines for designing VEs able to accommodate the identified individual differences. Several guidelines were formulated in order to make VEs more usable for different groups of users, for enabling them to experience greater presence and for supporting navigation. The latter aspect received considerable attention. A summary of the high and low level navigational rules captured in Chapters 8 and 9 has been used for describing the user model of navigation. This model has been used as a foundation for building an architecture of an adaptive VE able to support navigation of low spatial users. This general architecture was further refined, based on the original agent-based architecture of the ECHOES system.

Chapter 12

Conclusions

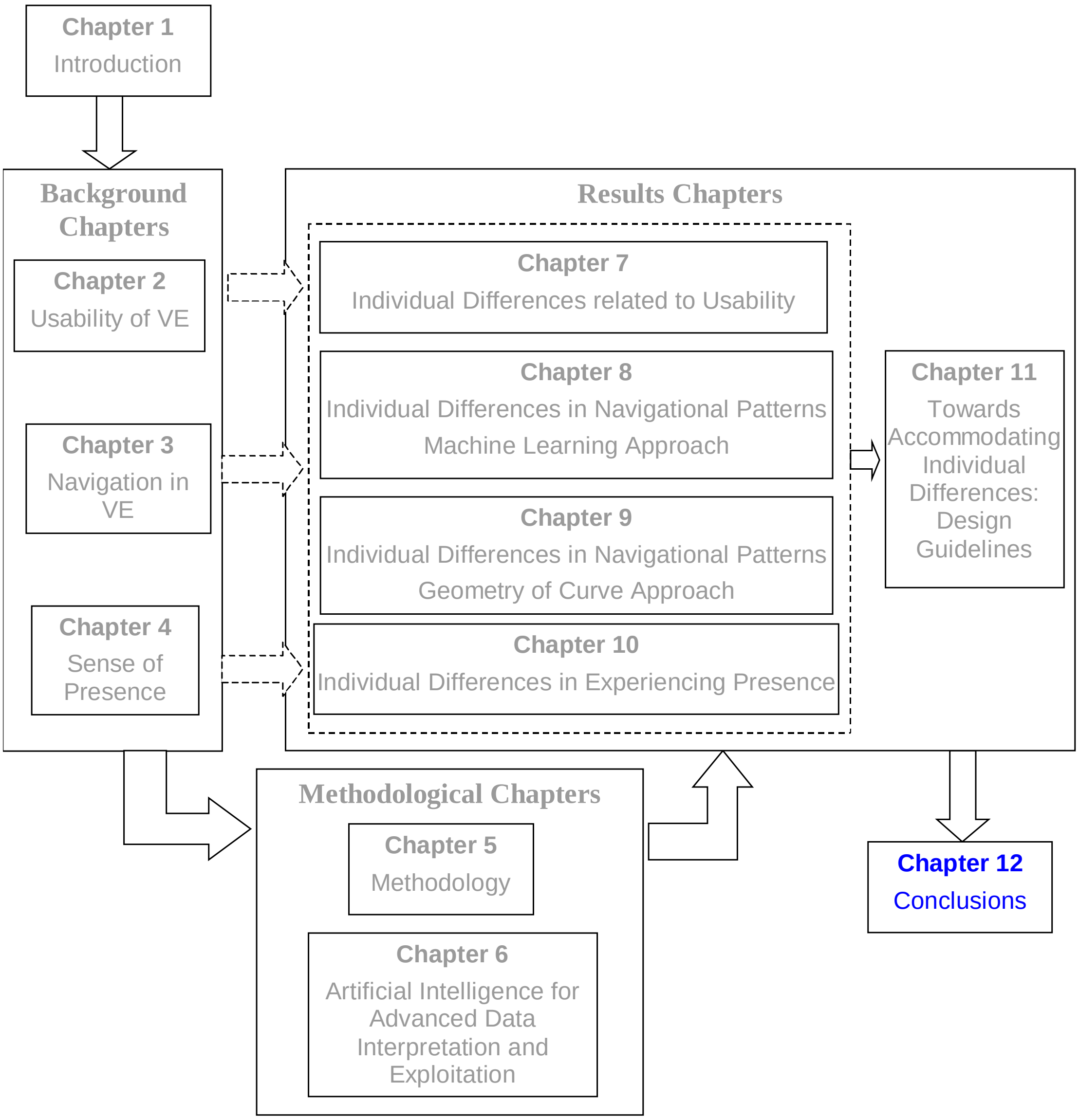

Figure 12.1: Road Map

This thesis investigated individual differences in navigating and experiencing presence in Virtual Environments (VEs). The need for such a study stemmed from the imbalance in current VE research, which has been mostly focused on technological factors rather than users' characteristics and individual differences. This chapter summarises the results in terms of the main contributions of this thesis and provides directions for future work.

In summarising the results, a starting point consists of the two original methodologies for investigating individual differences in navigating in VEs. A Self-Organising Map successfully clustered users' trajectories. It can be exploited to classify any new trajectory with classification accuracy higher than 85%. Among the five identified clusters, one comprised the trajectories of low spatial users. This enables the on-line identification of those users who need navigation assistance. The navigation support, which this work aims to offer, consists of enabling the access by low spatial users to efficient navigational rules employed by high spatial users. For this, a trajectory prediction model was developed. It successfully learned to predict the user's next location and heading, together with the nearest landmark (prediction accuracy above 68%). The best predictions of the Recurrent Neural Network were clustered. A rule induction algorithm was used to implicitly capture the rules associated with these clustered and embedded in trajectory paths. This methodology led to three high level navigational rules. It was complemented by another methodology that used Bézier curves for studying and modelling motion trajectories. Bézier curves provide a good fit to the data, and the results also indicate that the method provides a basis for the diagnosis of inefficient navigational patterns. It led to several low-level navigational rules.

These two methodologies focused on the user mental model of navigation, in order to build a user model of navigation in VEs. Such a model, consisting of navigational rules and strategies, can be harnessed to support efficient spatial behaviour. Several design guidelines have been proposed in order to accommodate these individual differences in navigational patterns. These guidelines are an initial step towards designing adaptive VEs. For this, the identified user model of navigation is a major prerequisite in building adaptive VEs for navigation assistance.

Another major direction followed within this thesis focused on the individual differences in experiencing presence. Results indicate that the more willing to experience presence, the more empathic, the more fantasy prone, the more absorbed, or the more imaginative the users are, the greater the sense of presence they will experience. Multiple regression led to a presence equation which can be used to predict presence based on these factors. These factors account for 45% of the variance in the sense of presence. Various design guidelines have been suggested for accommodating these individual differences. Such guidelines could prove beneficial in building VEs with the purpose of providing a heightened sense of presence.

12.1 Contributions

The thesis has achieved each of the study objectives presented in Chapter 1 and has tested the working hypotheses formulated within the result Chapters 7, 8, 9 and 10. There are several important contributions of the work presented in this thesis.

- An important contribution consists of a developed architecture for an adaptive VE, whose aim is to accommodate poor navigators in order to improve their spatial behaviour. A distinctive aspect of this architecture is the embodiment of a user model of navigation, rather than a simple set of navigational cues or maps which have been usually employed for all groups of users equally. This architecture bridges the gap between the existing models of navigation and the manner in which VEs are designed. When it comes to navigation assistance this gap is even larger, particularly because these models of navigation contain few details, in terms of rules, procedures or strategies. This creates difficulty in implementing those models into the design of a VE, and therefore few serious attempts have been made in this direction.
- The elaboration of such a user model of navigation is based on a set of navigational rules and strategies the capturing of which formed an extensive part of the thesis. Two original methodologies have been proposed and developed in this sense:
  - One methodology consists of a hybrid connectionist-symbolic system for modelling user's search behaviour. The non-declarative knowledge related to searching strategies has been investigated by analysing the trajectory paths using methods and techniques developed in the area of machine learning.
  - The other methodology consists of applying Bézier curves for modelling trajectories followed by users, while they navigate within the VE.
- The need to tailor the adaptive VE to different groups of users, constituted on the basis of their level of spatial abilities, implies the imperative need of identifying those groups. Classifying trajectories methodology allows the online and unobtrusive identification of these groups of users. This implies a link between users' patterns of spatial behaviour and their spatial performance on search tasks.
- The theoretical and empirical investigations of the impact carried by certain personality factors on sense of presence constitutes a significant contribution in the presence field. It fills a gap in current research and can provide a deeper understanding of presence phenomenon and users' characteristics related to it.
- The investigation of the relationship between presence and task performance suggested that it should be considered in the broader context of task characteristics and user gender. In addition, a particular role in this relationship seems to be played by the personality cognitive style. The study of this variable and its impact on presence–task performance relationship represents a novel and promising line of investigation.

12.2 Future Work

The work presented in this thesis represents significant contributions which are at the same time open to further investigations. Several potential avenues for further work building upon the results of this research are presented below.

- The most important future direction consists of implementing and evaluating the proposed architecture for building an adaptive VE able to identify and support inefficient navigators. Such a system will be based on the design guidelines which address the previously identified navigational rules and strategies. Such work should be carried out in the light of the principles of instructional design. Therefore, several usability tests should be conducted, with different versions of Adaptive ECHOES, for identifying which guidelines, combination of guidelines, or instructional strategies prove more efficient in supporting low spatial users' navigation.
- Future work should be carried out in order to refine the findings with respect to the identified navigational rules and strategies. Several directions can be followed in this sense:
    - Manipulating the spatial layout and landmark configuration for both indoor and outdoor spaces and analysing the impact it has on the employed strategies.
    - Refining the identified rules through expanding the analysis of individual pattern error of Recurrent Neural Network which was used to predict users' trajectories, from 10% top prediction to maybe 30% best predictions. For this, the sample of trajectories should be increased.
    - Employing different machine learning techniques for implicitly capturing the navigational rules and comparing their outcomes.
    - On-line refinement of the identified rules through the adaptive VE.
- The research presented in this thesis has been primarily dedicated to supporting inefficient navigators, in order to help them to improve their spatial behaviour and to increase their satisfaction while interacting with VEs. However, an adaptive VE should not be restrained to address only the limitations of low spatial users, but also the strengths of high spatial users. The latter case requires a "challenge strategy" to accommodate the specific needs of these users. Design guidelines whose implementation puts high demands on high spatial users will challenge them to deploy a larger set of cognitive resources for solving the tasks, which in turn can lead to more presence and/or a higher level of satisfaction with the system.
- Using VEs as a training arena for spatial skills is a promising start. Future studies should be conducted to understand under which conditions the benefits of learning efficient navigational rules within VEs are lessons to be applied in the real world.

- The navigational rules and the user model of navigation which are outcomes of this thesis can have an appealing potential for the field of robot navigation. The advanced spatial heuristics employed by humans can be utilised in or inspire the techniques developed for supporting robot navigation.
- The presence equation is far from being complete and further research is required in order to improve its power of prediction. Apart from the personality factors investigated in this thesis, others could be of interest, such as concentrated attention, suggestibility, critical thinking, sensation seeking, or particular skills required for the given tasks (see Section 4.3.2). It is conjectured that the human factors impacting on presence could be divided into two groups:
    - General human factors, such as those which constituted the core of this study, which ensure a greater sense of presence independent of the VE or task characteristics;
    - Specific human factors, which are task and environment dependent.

  This thesis focused on the general human factors which can impact on presence, while future work is required to address the task-specific user characteristics.

  In addition to the human factors, the impact of technological factors is the other major element of the prediction (see Section 4.3.1). In time, the third element to be incorporated into the equation for a better prediction of presence is that of media content (Lombard and Ditton, 1997; Kim and Biocca, 1997), which refers to the overall narrative depicted via a display system (Lessiter and Freeman, 2001). Willingness to experience presence is a determinant factor which can be enhanced by the media content. To conclude, the identified presence equation should be viewed as a simplified form of the general presence equation:

$$\begin{aligned}\text{Presence} &= \alpha \cdot (\text{General human factors}) + \beta \cdot (\text{Task specific human factors}) + \\ &\quad \gamma \cdot (\text{Technological factors}) + \delta \cdot (\text{Media content}) \qquad (12.1)\end{aligned}$$

- Another future direction will focus on the relationship between the users' characteristics and their impact on task performance. Particular skills which enhance task performance will also be considered, while the independent variables will be defined in terms of task characteristics.
- The relationship between presence and task performance proved again to be difficult to establish, suggesting that it should be considered in the broader context of task characteristics and user gender. Attempts to understand this relationship should come from various perspectives. Apart from personality cognitive style which seems to be a promising direction, other sets of skills, such as spatial abilities, and characteristics of the VE can be considered.
- In the attempt to control extraneous variables which may impact on the variables

of interest, the tasks consisted only of naive or primed search. They were solitary tasks, highly perceptual which allowed users a relatively reduced control over the interaction and over the VE. Future work should consider and examine collaborative tasks offering insights into the impact of user's characteristics upon sense of presence, system usability and performance on spatial tasks.

The work carried out in this thesis has deepened the understanding of how people comprehend the space. It has exploited these outcomes for designing VEs for navigation support. Such kind of research ultimately aims to make VEs better places to play, work or learn and to offer a pleasant, satisfying and rewarding experience.

Bibliography

Aamodt, A. and Plaza, E. (1994). Case-based reasoning: Foundational issues, methodological variations, and system approaches. *AI Communications*, 7(1):39–52.

Adam, J. (1993). Virtual reality is for real. *IEEE Spectrum*, 30(10):30–33.

Adobe Systems Incorporated (1985). *PostScript Language Reference Manual*.

Aggarwa, J. and Cai, Q. (1997). Human motion analysis: A review. In *Proceedings IEEE Nonrigid and Articulated Motion Workshop*, pages 428–440.

Agrawala, M. and Stolte, C. (2001). Rendering effective route maps: Improving usability through generalization. In *Computer Graphics: A Quarterly Report of ACM SIGGRAPH*, volume 18, pages 241–250.

Aha, D. (1990). *A Study of Instance-Based Learning Algorithms for Supervised Learning Tasks: Mathematical, Empirical, and Psychological Evaluations*. PhD thesis, Department of Information and Computer Science, University of California.

Allen, G. (1982). The organization of route knowledge, new directions for child development. *Children's Conceptions of Spatial Relationships*, 15:31–39.

Alley, G. and Deshler, D. (1979). *Teaching the Learning Disabled Adolescent: Strategies and Methods*. Love, Denver.

Allport, G. (1937). *Personality—A Psychological Interpretation*. Henry Holt and Company, New York, NY.

Allport, G. (1966). Traits revisited. *American Psychologist*, 21:1–10.

Amant, R. and Riedl, M. (2001). A practical perception substrate for cognitive modelling in HCI. *International Journal of Human Computer Studies*, 55(1):15–39.

Ambrosini, V. and Bowman, C. (2001). Tacit knowledge: Some suggestions for operationalization. *Journal of Management Studies*, 38(6):811–829.

Anderberg, M. (1973). *Cluster Analysis for Applications*. Academic Press, New York, NY.

Anderson, J. (1976). *Language, Memory, and Thought.* Lawrence Erlbaum, Hillsdale, NJ.

Anderson, J. (1983). *The Architecture of Cognition.* Hardvard University Press, Cambridge, MA.

Anderson, J. (2000). *Cognitive Psychology and Its Implications.* Worth Publishing, New York, NY.

Arakawa, A., Hyyama, M., Emura, T., and Kagami, Y. (1995). Trajectory generation for wheeled mobile robot based on landmarks. In *Proceedings of IEEE International Conference on Systems, Man and Cybernetics*, volume 2, pages 1273–1278.

Arleo, A., Smeraldi, F., Hug, S., and Gerstner, W. (2000). *Advances in Neural Information Processing Systems*, volume 13, chapter Place cells and spatial navigation based on vision, path integration, and reinforcement learning, pages 89–95. MIT Press.

Atkins, H., Moore, D., Hobbs, D., and Sharpe, S. (2001). Learning style theory and computer mediated communication. In *Proceedings ED MEDIA 2001.*

Atkins, M. and Steitz, J. (2002). The assessment of empathy: An evaluation of the interpersonal reactivity index. URL: `http://www.uu.edu/union/academ/tep/research/atkins.htm` (version current as of February 06, 2002).

Aukstakalnis, S. and Blatner, D. (1992). *Silicon Mirage: The Art and Science of Virtual Reality.* Peachpit Press, Berkeley.

Avouris, N. (2001). An introduction to software usability. In *Proceedings of 8th Panhellenic Conference on Informatics, Workshop on Software Usability*, volume 2, pages 514–522, Athens. Livanis Publisher.

Balcisoy, S., Torre, R., Ponder, M., Fua, P., and Thalmann, D. (2000). Augmented reality for real and virtual humans. In *Proceedings of CGI 2000*, pages 303–308. IEEE Computer Society Press.

Barber, T. and Wilson, S. (1979). The Barber suggestibility scale and the creative imagination scale: Experimental and clinical applications. *The American Journal of Clinical Hypnosis*, 21(2-3):84–108.

Barfield, W., Zeltzer, D., Sheridan, T., and Slater, M. (1995). Presence and performance with virtual environments. In Barfield, W. and Furness, T., editors, *Virtual Environments and Advanced Interface Design*, pages 473–513. Oxford Press.

Bartels, R., Beatty, J., and Barsky, B. (1998). *An Introduction to Splines for Use in Computer Graphics and Geometric Modelling*, chapter Bézier Curves, pages 211–245. Morgan Kaufmann, San Francisco, CA.

Bellifemine, F., Poggi, A., and Rimassa, G. (1999). JADE—a FIPA compliant agent framework. In *Proceedings of the International Conference and Exhibition of the Practical Application of Intelligent Agents and Multiagents*, pages 97–108.

Benford, S., Bowers, J., Chandler, P., Ciolfi, L., Flintham, M., Fraser, M., Greenhalgh, C., Hall, T., Hellstrom, S., Izadi, S., Rodden, T., Schnadelbach, H., and Taylor, I. (2001). Unearthing virtual history: Using diverse interfaces to reveal hidden virtual worlds. In *Proceedings UBICOMP*, pages 225–231, Atlanta. ACM Press.

Benford, S., Bowers, J., Fahlén, L., Mariani, J., and Rodden, T. (1994). Supporting co-operative work in virtual environments. *The Computer Journal*, 37(8):408–414.

Benford, S., Brown, C., Reynard, G., and Greenhalgh, C. (1996). Shared spaces: Transportation, artificiality and spatiality. In *Proc. ACM Conference on Computer Supported Cooperative Work (CSCW'96)*, pages 77–86. ACM Press.

Benford, S. and Fahlén, L. (1993). A spatial model of interaction in virtual environments. In *Proc. Third European Conference on Computer Supported Cooperative Work (ECSCW'93)*, pages 109–124, Deventer, The Netherlands. Kluwer.

Benyon, D. (1993). Accommodating individual differences through an adaptive user interface. In Schneider-Hufschmidt, M., Khme, T., and Malinowski, U., editors, *Adaptive User Interfaces—Results and Prospects*, pages 149–165. Elsevier Science Publications, Amsterdam.

Benyon, D. and Murray, D. (1993). Applying user modelling to human–computer interaction design. *Artificial Intelligence Review*, 6:43–69.

Berendt, B. and Brenstein, E. (2001). Visualizing individual differences in web navigation: STRATDYN, a tool for analyzing navigation patterns. *Behavior Research Methods, Instruments, and Computers*, 33:243–257.

Bergenti, F. and Poggi, A. (2001). LEAP: A FIPA platform for handheld and mobile devices. In *Proceedings of the 8th International Workshop on Agent Theories, Architectures, and Languages (ATAL)*, pages 436–446.

Berger, C. and Kam, R. (2003). Definitions of instructional design. URL: `http://www.umich.edu/~ed626/define.html` (version current as of 23 Nov. 2003). Copyright 1996 The University of Michigan.

Berry, D. (1987). The problem of implicit knowledge. *Expert Systems*, 4:144–151.

Biocca, F. (1997). The cyborg's dilemma: Progressive embodiment in virtual environment. *Journal of Computer—Mediated Communication*, 3(2).

Blaikie, N. (1991). A critique of the use of triangulation in social research. *Quality and Quantity*, 25:115–136.

Bliss, J., Tidwell, P., and Guest, M. (1997). The effectiveness of virtual reality for administering spatial navigation training to firefighters. *Presence, Teleoperators and Virtual Environments*, 6(1):73–86.

Bloom, B. (1956). *Taxonomy of Educational Objectives.* David McKay Co., New York, NY.

Bock, R. K. and Krischer, W. (1998). *Data Analysis BriefBook.* Springer, Berlin. URL: `http://rkb.home.cern.ch/rkb/AN16pp/node1.html` (version current as of May 02, 2003).

Booth, P. (1989). *An Introduction to Human–Computer Interaction.* Lawrence Erlbaum Associates, London.

Boswell, J. (2001). User—centered iterative design of a collaborative virtual environment. Master's thesis, Department of Computer Science, Naval Postgraduate School.

Boulic, R., Noser, H., and Thalmann, D. (1994). Automatic derivation of curved human walking trajectories from synthetic vision. In *Proceedings IEEE Computer Animation*, pages 93–103.

Bourke, P. (1998). Calculating the area and centroid of a polygon. URL: `http://astronomy.swin.edu.au/~pbourke/geometry/polyarea` (version current as of April 07, 2003).

Bowers, J., O'Brien, J., and Pycock, J. (1996). Practically accomplishing immersion: Cooperation in and for virtual environments. In *Proceedings of ACM Conference on Computer Supported Cooperative Work*, pages 380–389, Cambridge, MA. ACM Press.

Bowman, D. (1999). *Interaction Techniques for Common Tasks in Immersive Virtual Environments.* PhD thesis, Department of Computer Science, Georgia Institute of Technology.

Bowman, D., Davis, E., Badre, A., and Hodges, L. (1999). Maintaining spatial orientation during travel in an immersive virtual environment. *Presence: Teleoperators and Virtual Environments*, 8(6):618–631.

Bradtke, S. and Barto, A. (1996). Linear least-squares algorithms for temporal difference learning. *Machine Learning*, 22:33–57.

Brusilovsky, P. and Maybury, M. (2002). From adaptive hypermedia to the adaptive web. *Communications of the ACM*, 45(5):31–33.

Campbell, D. and Fiske, D. (1959). Convergent and discriminant validation by the multitrait-multimethod matrix. *Psychological Bulletin*, 56:81–104.

Campbell, J. (1998). *Map Use and Analysis.* McGraw-Hill, Boston, MA.

Cañas, J., Salmerón, L., Antolí, A., Fajardo, I., C. Chisalita, C., and Escudero, J. (2003). Differential roles for visuospatial and verbal working memory in the construction of mental models of physical systems. *International Journal of Cognitive Technology*, pages 45–53.

Chaudhari, A., Bragg, R., Alexander, E., and Andriacchi, T. (2001). A video-based, markerless motion tracking system for biomechanical analysis in an arbitrary environment. In *BED Bioengineering Conference ASME*, volume 50, pages 777–778.

Chen, C. (2000). Individual differences in a spatial-semantic virtual environment. *Journal of the American Society for Information Science*, 51(6):529–542.

Chen, C., Czerwinski, M., and Macredie, R. (2000). Individual differences in virtual environments—introduction and overview. *Journal of the American Society for Information Science*, 51(6):499–507.

Chen, C. and Rada, R. (1996). Interacting with hypertext: A meta—analysis of experimental studies. *Human–Computer Interaction*, 11(2):125–156.

Chen, J. and Stanney, K. (1999). A theoretical model of wayfinding in virtual environments: Proposed strategies for navigational aiding. *Presence: Teleoperators and Virtual Environments*, 8(6):671–685.

Chen, S. and Ford, N. (1997). Towards adaptive information systems: Individual differences and hypermedia. *Information Research*, 3(2).

Child, D. (1970). *The Essentials of Factor Analysis.* Holt, Rinehart and Winston, London.

Chin, J., Diehl, V., and Norman, K. (1988). Development of an instrument measuring user satisfaction of the human–computer interface. In *Proceedings ACM CHI*, pages 213–218.

Christos, S. (1996). What is a neural network? *Surprise On-Line Journal*, 1.

Chung, S. and Hahn, J. (1999). Animation of human walking in virtual environments. In *Proceedings of Computer Animation*, pages 4–15.

Churchill, E. F. and Snowdon, D. (1998). Collaborative virtual environments: An introductory review of issues and systems. *Virtual Reality*, 3(1):3–15.

Clark, A. (1997). *Being There: Putting Brain, Body and World Together Again.* MIT Press, Cambridge, MA.

Cohen, L. and Manion, L. (1986). *Research Methods in Education.* Croom Helm, London.

Collier, R., O'Hare, G., Lowen, T., and Rooney, C. (2003). *Third International Central & Eastern European Conference on Multi-Agent Systems, CEEMAS 2003*, chapter Beyond Prototyping in the Factory of Agents, pages 383–393. Lecture Notes in Computer Science. Springer Verlag, Berlin.

Crawford, H. (1982). Hypnotizability, daydreaming styles, imagery vividness and absorption: A multidimensional study. *Journal of Personality and Social Psychology*, 42(5):915–926.

Cristianini, N. and Shawe-Taylor, J. (2000). *An Introduction to Support Vector Machines (and Other Kernel-Based Learning Methods).* Cambridge University Press, Cambridge.

Csikszentmihalyi, M. (1990). *The Psychology of Optimal Experience.* Harper and Row, New York, NY.

Cunningham-Atkins, H., Moore, D., and Hobbs, D. (2003). Learning style theory and computer mediated communication. In *Proceedings of ELSIN 2003 Eighth Annual Learning Styles Conference: Bridging Theory & Practice,.*

Curry, L. (1983). An organization of learning styles theory and constructs. *ERIC Document, 235-185.*

Czerwinski, M., Tan, D., and Robertson, G. (2002). Women take a wider view. In *Proceedings of CHI 2002*, pages 195–202. ACM Press.

Damsgaard, M., Rasmussen, J., Tørholm, S., Surma, E., and Zee, M. (2001). AnyBody—a system for biomechanical analysis and ergonomic design. In *Proceedings of Max Planck Workshop on Engineering Design Optimization.*

Dana, R. (2000). *Handbook of Cross-Cultural and Multicultural Personality Assessment.* Lawrence Erlbaum Associates, Mahwah, NJ.

Darken, R. (1995). Wayfinding in large-scale virtual worlds. In *Proceedings of SIGCHI*, pages 45–46. ACM Press.

Darken, R., Allard, T., and Achille, L. (1998). Spatial orientation and wayfinding in large-scale virtual spaces: An introduction. *Presence, Teleoperators and Virtual Environments*, 7(2):101–107.

Darken, R. and Banker, W. (1998). Navigating in natural environments: A virtual environment training transfer study. In *Proceedings of VRAIS 98*, pages 12–19.

Darken, R. and Peterson, B. (2002). Spatial orientation, wayfinding, and representation. In Stanney, K., editor, *Handbook of Virtual Environments—Design, Implementation, and Applications*, pages 493–518. Lawrence Erlbaum Associates, New Jersey, NJ.

Darken, R. and Sibert, J. (1996a). Navigating large virtual spaces. *International Journal of Human–Computer Interaction*, 8(1):49–72.

Darken, R. and Sibert, J. (1996b). Wayfinding strategies and behaviors in large virtual environments. In *Conference Proceedings CHI '96, Human Factors in Computing Systems*, pages 142–149.

Davis, M. (1980). A multidimensional approach to individual differences in empathy. *Catalog of selected document in psychology*, 10(4):1–18.

Davis, M. (1983). Measuring individual differences in empathy: Evidence for a multidimensional approach. *Journal of Personality and Social Psychology*, 44:113–126.

Davis, M. (1994). *Empathy: A social psychological approach.* Westview Press, Oxford.

Dawson, M. and Shamanski, K. (1994). Connectionism, confusion and cognitive science. *Journal of Intelligent Systems*, 4:215–262.

Delahunty, T. (2001). ECHOES: A cohabited virtual training environment. Master's thesis, Department of Computer Science, University College Dublin.

Dieberger, A., Dourish, P., Höök, K., Resnick, P., and Wexelblat, A. (2000). Social navigation: Techniques for building more usable systems. *Interactions*, 7(6):36–45.

Dijk, B. V., Akker, R. O. D., Nijholt, A., and Zwiers, J. (2003). Navigation assistance in virtual worlds. *Informing Science, Special Series on Community Informatics*, 6:115–125.

Downs, R. and Stea, D. (1973). Cognitive maps and spatial behavior: Process and products. In Downs, R. and Stea, D., editors, *Image and Environment*, pages 8–26. Aldine Publishing Company, Chicago, IL.

Draper, J., Kaber, D., and Usher, J. (1998). Telepresence. *Human Factors*, 40(3):354–375.

Dreyfus, H. (2000). Telepistemology: Descarte's last stand. In Goldberg, K., editor, *The Robot in the Garden: Telerobotics and Telepistemology in the Age of the Internet.* MIT Press, Cambridge, MA.

Dubitzky, W., Granzow, M., and Berrar, D. (2001). Comparing symbolic and subsymbolic machine learning approaches to classification of cancer and gene identification. In Lin, S. and Johnson, K., editors, *Methods of Microarray Data Analysis: Papers from CAMDA'00*, pages 151–166. Kluwer Academic Publishers.

Duffy, B., O'Hare, G., Martin, A., Bradley, J., and Schön, B. (2003). Agent chameleons: Agent minds and bodies. In *Proceedings 16th International Conference on Computer Animation and Social Agents (CASA 2003).* IEEE Computer Society Press.

Dumas, J. (1998). Usability testing methods: Subjective measures. *Common Ground*, 8(3):5–10.

Durlach, N., Allen, G., Darken, R., Garnett, R., Loomis, J., Templeman, J., and Von-Wiegand, T. (2000). Virtual environments and the enhancement of spatial behavior: A proposed research agenda. *Presence: Teleoperators and Virtual Environments*, 9(6):593–615.

Education, S. (1991). Instructional approaches: A framework for professional practice. URL: `http://www.sasked.gov.sk.ca/docs/policy/approach` (version current as of 25 Nov. 2003).

Egan, D. (1988). Individual differences in human–computer interaction. In Helander, M., editor, *Handbook of Human–Computer Interaction*, pages 543–568. Elsevier Science, Amsterdam.

Egan, D. and Gomez, L. (1985). Assaying, isolating, and accommodating individual differences in learning a complex skill. In Dillon, R., editor, *Individual Differences in Cognition*, pages 173–217. Academic Press, Orlando.

Ellis, D., Ford, N., and Wood, F. (1992). Hypertext and learning styles. Technical report, Learning Technology Unit. Sheffield: Employment Department, Cambridge, MA.

Ellis, N. (1994). *Implicit and Explicit Learning of Languages.* Academic Press, San Diego, CA.

Ellis, R. and Humphreys, G. (1999). *Connectionist Psychology: A Text with Readings.* Psychology Press, Hove.

Ellis, S. (1996). Presence of mind: A reaction to Thomas Sheridan's "further musings on the psychphysics of presence". *Presence: Teleoperators and Virtual Environments*, 5(2):247–259.

Elman, J. (1990). Finding structure in time. *Cognitive Science*, 14:179–211.

Elman, J. (1991). Distributed representations, simple recurrent networks, and grammatical structure. *Machine Learning*, 7(2-3):195–226.

Ericcson, K. and Simon, H. A. (1984). *Protocol Analysis.* MIT Press, Cambridge, MA.

Esposito, C. (1996). User interfaces for virtual reality systems. In *In Human Factors in Computing Systems, CHI '96 Conference Tutorial Notes.* ACM Press.

Farthing, W. (1992). *The Psychology of Consciousness.* Prentice-Hall, Englewood Cliffs, NJ.

Fausett, L. (1994). *Fundamentals of Neural Networks.* Prentice Hall, Englewood Cliffs, NJ.

Felder, R. and Silverman, L. (1988). Learning and teaching styles in engineering education. *Engineering Education*, 78(7):674–681.

Fernie, K. and Richards, J. (2002). *Creating and Using Virtual Reality: A Guide for the Arts and Humanities.* URL: `http://vads.ahds.ac.uk/guides/vr\_guide/glossary.html` (version current as of March 10, 2003).

Finin, T. (1989). GUMS—a general user modelling shell. In Wahlster, W. and Kobsa, A., editors, *User Models in Dialog Systems*, pages 4–33. Springer-Verlag, Berlin.

Finlay, J. and Beale, R. (1992). Pattern recognition and classification in dynamic and static user modelling. In Beale, R. and Finlay, J., editors, *Neural Networks and Pattern Recognition in Human Computer Interaction*, pages 65–89. Ellis Horwood, Chichester.

FIPA (2003). The foundation for intelligent physical agents. URL: `http://www.fipa.org` (version current as of November 23, 2003).

Fischer, G. (2001). User modeling in human–computer interaction. *User Modeling and User-Adapted Interaction*, 11(1-2):65–86.

Fleming, J. (1998). *Web Navigation: Designing the User Experience.* OReilly and Associates, Sebastopol, CA.

Fodor, J. and Pylyshyn, Z. (1988). Connectionism and cognitive architecture: A critical analysis. *Cognition*, 3:3–71.

Forbus, K. (1984). Qualitative process theory. *Artificial Intelligence*, 168:24–85.

Ford, L., Williams, M., and Morris, C. (1995). Intelligent adaptive systems for information delivery in the electronic library. In Collier, M. and Arnold, K., editors, *Electronic Library and Visual Information Research (ELVIRA 2)*, pages 137–143. Aslib, London.

Ford, N. (1985). Learning styles and strategies of post-graduate students. *British Journal of Educational Technology*, 16(1):65–77.

Ford, N. (2000). Cognitive styles and virtual environments. *Journal of American Society for Information Science*, 51(6):543–557.

Gabbard, J. and Hix, D. (1997). *Taxonomy of Usability Characteristics in Virtual Environments.* Virginia Polytechnic Institute, Blackenburg.

Gabbard, J., Swartz, K., Richey, K., and Hix, D. (1999). Usability evaluation techniques: A novel method for assessing the usability of an immersive medical visualization VE. In *VWSIM '99 Proceedings*, pages 165–170, San Fransisco, CA.

Gagné, R. and Briggs, L. (1974). *Principles of Instructional Design.* Holt, Rinehart, and Winston, New York, NY.

Garson, D. (2002). PA 765 statnotes textbook 2002. URL: `http://www2.chass.ncsu.edu/garson/pa765/statnote.html` (version current as of March 07,2002).

Gelder, T. V. and Port, R. (1995). It's about time: an overview of the dynamical approach to cognition. In Gelder, T. V. and Port, R., editors, *Mind as Motion: Explorations in the Dynamics of Cognition*, pages 1–43. MIT Press, Cambridge, MA.

Gentner, D. (2002). Psychology of mental models. In Smelser, N. and Bates, P., editors, *International Encyclopedia of the Social and Behavioral Sciences*, pages 9683–9687. Elsevier Science, Amsterdam.

Gerrig, R. (1993). *Experiencing Narrative Worlds: On the Psychological Activities of Reading.* Yale University Press, New Haven, CT.

Ghiselli-Crippa, T. (2000). *Spatial and Temporal Factors in the Acquisition of Spatial Information: A Connectionist Model.* PhD thesis, School of Information Sciences, University of Pittsburgh.

Gilmore, D. and Self, J. (1988). The application of machine learning to intelligent tutoring systems. In Self, J., editor, *Artificial Intelligence and Human Learning*, pages 179–196. Chapman and Hall, London.

Goerger, S., Darken, R., Boyd, M., Gagnon, T., Liles, S., Sullivan, J., and Lawson, J. (1998). *Proceedings of the 16th Applied Behavioral Sciences Symposium*, chapter Spatial Knowledge Acquisition from Maps and Virtual Environments in Complex Architectural Spaces, pages 6–10. U.S. Air Force Academy, Colorado Springs, CO.

Goguen, J. and Linde, C. (1993). Techniques for requirements elicitation. In Fickas, S. and Finkelstein, A., editors, *Proceedings, Requirements Engineering.* IEEE Computer Society Press.

Golberg, K. (2000). Introduction: The unique phenomenon of a distance. In Goldberg, K., editor, *The Robot in the Garden: Telerobotics and Telepistemology in the Age of the Internet.* MIT Press, Cambridge, MA.

Goldsmith, M. (1998). Connectionist modeling and theorizing: Who does the explaining and how? *Psycoloquy*, 9(18).

Golledge, G. (1999). Human cognitive maps and wayfinding. In Golledge, G., editor, *Wayfinding Behaviour*, pages 1–45. John Hopkins University Press, Baltimore.

Golledge, R. (1996). Geographical theories. *International Social Science Journal, Geography: State of the art I–The environmental dimension*, 150:461–476.

Goodenough, D. (1976). The role of individual differences in field dependence as a factor in learning and memory. *Psychological Bulletin*, 83:675–694.

Grant, A. (1990). *Modelling Cognitive Aspects of Complex Control Tasks.* PhD thesis, Department of Computer Science, University of Strathclyde, Glasgow.

Gravetter, F. and Wallnau, L. (1999). *Statistics for the Behavioral Sciences.* Wadsworth Publishing, Belmont, CA, 5 edition.

Gray, A. (1998). *Modern Differential Geometry of Curves and Surfaces with Mathematica.* CRC Press, Boca Raton.

Greco, A. (1998). Connectionist models can reveal good analogies. *Psycoloquy: Psycoloquy*, 9(47).

Green, C. (1998). Are connectionist models theories of cognition? *Psycoloquy*, 9(4).

Greenhalgh, C. and Benford, S. (1995). MASSIVE: A virtual reality system for teleconferencing. *ACM Transactions on Computer Human Interfaces*, 2(3):239–261.

Grigorenko, E. (2000). Cognitive style. In Kazdin, A., editor, *Encyclopedia of Psychology*, pages 163–166. Oxford University Press, Oxford.

Grimson, W., Stauffer, C., Lee, L., and Romano, R. (1998). Using adaptive tracking to classify and monitor activities in a site. In *Proceedings IEEE Conference on Computer Vision and Pattern Recognition*, pages 22–31.

Guilford, J. and Zimmerman, W. (1948). The Guilford–Zimmerman aptitude survey. *Journal of Applied Psychology*, 32:24–34.

Guinan, T., O'Hare, G., and Doikov, N. (2000). ENTER: The personalisation and contextualisation of 3-dimensional worlds. In *Proceedings of Eight Euromicro Workshop on Parallel and Distributed Processing*, pages 142–149. IEEE Computer Society Press.

Guthrie, E. (1952). *The Psychology of Learning.* Harper et Row, New York, NY.

Hagner, D., Watta, P., and Hassoun, M. (1999). Comparison of recurrent neural networks for trajectory generation. In Medsker, L. and Jain, L., editors, *Recurrent Neural Networks: Design and Applications*, pages 243–276. CRC Press, Boca Raton.

Haines, E. (1994). Point in polygon strategies. In Heckbert, P., editor, *Graphics Gems IV*, pages 24–46. Academic Press, Boston, MA.

Hanisch, K. (1991). Cognitive representations, control, and understanding of complex systems: A field study focusing on components of users' mental models and expert/novice differences. *Ergonomics*, 34(8):1129–1145.

Hanson, S. and Burr, D. (1990). What connectionist models learn: Learning and representation in connectionist networks. *Behavioral and the Brain Science*, 13:471–518.

Harm, D. (2002). Motion sickness: Neurophysiology, physiological correlates, and treatment. In Stanney, K., editor, *Virtual Environments Handbook*, pages 637–661. Lawrence Erlbaum Associates.

Hart, R. and Moore, G. (1973). The development of spatial cognition: A review. In Downs, R. and Stea, D., editors, *Image and Environment*, pages 246–288. Aldine Publishing Company, Chicago, IL.

Haykin, S. (1994). *Neural Networks: A Comprehensive Foundation*. Prentice-Hall, New Jersey, NJ.

Heeter, C. (1992). Being there: The subjective experience of presence. *Presence: Teleoperators and Virtual Environments*, 1(2):262–271.

Heeter, C. (2003). Reflections on real presence by a virtual person. *Presence Teleoperators and Virtual Environments*, 12(4):335–345.

Heiman, G. (2001). *Understanding Research Methods and Statistics*. Houghton Mifflin Company, Boston, MA.

Heinlein, R. (1950). *Waldo and Magic*. Del Rey, New York, NY.

Henderson, L., Putt, I., and Coombs, G. (2002). Mental models of teaching and learning with the WWW. In *Winds of Change in the Sea of Learning. Proceedings of the 19th Annual Conference of the Australasian Society for Computers in Learning in Tertiary Education*, Auckland, New Zealand. UNITEC Institute of Technology.

Hickey, B. (1994). Fitting data of arbitrary dimension with B-splines and applications to colour calibration. Master's thesis, School of Computer Science, University of Waterloo.

Hilgard, J. (1979). *Personality and hypnosis: A study of imaginative involvement*. University of Chicago Press, Chicago, IL.

Hirose, M. (1996). The synthesis of realistic sensations. In *Virtual Reality World 96 Conference Proceedings*, Stuttgart, Germany.

Hix, D. and Hartson, H. (1993). *Developing User Interfaces*. John Wiley & Sons, Inc., New York, NY.

Horn, B. (1983). The curve of least energy. *ACM Transactions on Mathematical Software*, 9(4):441–460.

Hudlicka, E. (1996). Requirements elicitation with indirect knowledge elicitation techniques: Comparison of three methods. In *Proceedings of the Second International Conference on Requirements Engineering*, pages 4–11. IEEE Computer Society Press.

Hutchins, E. (1983). Understanding micronesian navigation. In Gentner, D. and Stevens, A., editors, *Mental Models*, pages 191–225. Erlbaum, Hillsdale, NJ.

Isdale, J. (2002). What is virtual reality? A homebrew introduction and information resource list. URL: `http://www.isdale.com/jerry/VR/WhatIsVR.html` (version current as of March 07, 2002).

Isensee, S. and Vredenburg, K. (2000). User—centered design. In Clements, P., editor, *Constructing Superior Software*. Macmillan Technical Publishing, Indianapolis, IN.

ISO (1997). *Ergonomic Requirements for Office Work with Visual Display Terminals*. International Organization for Standardization.

Jacobs, W., Thomas, K., Laurence, H., and Nadel, L. (1998). Place learning in virtual space II: Topological relations as one dimension of stimulus control. *Learning and Motivation*, 29:288–308.

Jain, A., Murty, M., and Flynn, P. (1999). Data clustering: A review. *ACM Computing Surveys*, 31(3):264–323.

James, D. and Miikkulainen, R. (1995). SARDNET: A self organizing feature map for sequences. In Tesauro, G., Touretzky, D., and Leen, T., editors, *Proceedings of the Advances in Neural Information Processing Systems*, pages 577–584, Cambridge, MA. MIT Press.

Jameson, A. (2003). Adaptive interfaces and agents. In Jacko, J. and Sears, A., editors, *Human–Computer Interaction Handbook*, pages 316–318. Erlbaum, Mahwah, NJ.

Johnson, N. and Hogg, D. C. (1996). Learning the distribution of object trajectories for event recognition. *Image and Vision Computing*, 14:609–615.

Johnson-Laird, P. (1981). Mental models of meaning. In Joshi, A., Webber, B., and Sag, I., editors, *Elements of Discourse Understanding*, pages 106–126. Cambridge University Press, Cambridge.

Jolliffe, I. (1986). *Principal Component Analysis*. Springer-Verlag, New York, NY.

Jul, S. and Furnas, G. W. (1997). Navigation in electronic worlds: Workshop report. *SIGCHI Bulletin*, 29(4):44–49.

Jung, C. (1971). Psychological types. In Ress, L. and McGuire, W., editors, *The Collected Works of C.G. Jung*, volume 6. Princeton University Press, Princeton.

Kaber, D., Draper, J., and Usher, J. (2002). Influence of individual differences on virtual reality application design for individual and collaborative immersive virtual environments. In Stanney, K., editor, *The Handbook of Virtual Environments: Design, Implementation and Applications*, pages 379–402. Lawrence Erlbaum & Associates, Mahwah, NJ.

Kangas, J. (1990). Time-delayed self-organizing maps. In *Proceedings of the International Joint Conference on Neural Networks*, pages 331–336.

Kaplan, S. (1973). Cognitive maps in perception and thought. In Downs, R. and Stea, D., editors, *Image and Environment*, pages 63–86. Aldine Publishing Company, Chicago, IL.

Kappen, H. (1995). Deterministic learning rules for boltzmann machines. *Neural Networks*, 8(4):537–548.

Kaski, S. (1997). *Data Exploration Using Self-Organizing Maps.* PhD thesis, Department of Computer Science and Engineering, Helsinki University of Technology.

Kaur, K. (1998). *Designing Virtual Environments for Usability.* PhD thesis, Centre for Human–Computer Interface Design, City University, London.

Keinonen, T. (1998). *One-Dimensional Usability — Influence of Usability on Consumers' Product Preference.* PhD thesis, Industrial Design, University of Art and Design Helsinki.

Kelly, G. (1955). *The Psychology of Personal Constructs.* Norton, New York, NY.

Khatib, M., Jaouni, H., Chatila, R., and Laumond, J. (1997). Dynamic path modification for car-like nonholonomic mobile robots. In *Proceedings of IEEE International Conference on Robotics and Automation*, pages 2920–2925.

Kieras, D. and Bovair, S. (1984). The role of mental model in learning to operate a device. *Cognitive Science*, 8:255–273.

Kim, T. and Biocca, F. (1997). Telepresence via television: Two dimensions of telepresence may have different connections to memory and persuasion. *Journal of Computer—Mediated Communication*, 3(2).

Kirakowski, J. and Corbett, M. (1990). Effective methodology for the study of HCI. In Bullinger, H. and Polson, P., editors, *Human Factors in Information Technology*, volume 5. Elsevier, Amsterdam: North-Holland.

Klatzky, R. (1998). Allocentric and egocentric spatial representations: Definitions, distinctions, and interconnections. In Freksa, C. and Habel, C., editors, *Spatial Cognition: An Interdisciplinary Approach to Representing and Processing Spatial Knowledge*, volume 1404 of *Lecture Notes in Computer Science*, pages 1–18. Springer-Verlag, Berlin.

Knuth, D. (1986). *The METAFONTbook.* Addison Wesley Publishing Company, Reading, MA.

Kobsa, A. (1994). User modeling and user—adapted interaction. In *Proceedings of the CHI'94 Conference Companion on Human Factors in Computing Systems*, pages 415–416.

Kohonen, T. (2001). Self-organizing maps. In *Springer Series in Information Sciences*, volume 30. Springer-Verlag, Berlin.

Kohonen, T., Hynninen, J., Kangas, J., and Laaksonen, J. (1996). SOM PAK: The self-organizing map program package. Technical Report A31, Helsinki University of Technology, Laboratory of Computer and Information Science.

Kohonen, T., Hynninen, J., Kangas, J., Laaksonen, J., and Torkkola, K. (1995). LVQ PAK: The learning vector quantization program package. Technical Report 30, Helsinki University of Technology, Laboratory of Computer and Information Science.

Koskela, T., Varsta, M., Heikkonen, J., and Kaski, K. (1998). Time series prediction using recurrent SOM with local linear models. *International Journal of Knowledge-Based Intelligent Engineering Systems*, 2(1):60–68.

Krieg-Brückner, B., Röfer, T., Carmesin, H., and Müller, R. (1998). A taxonomy of spatial knowledge for navigation and its application to the bremen autonomous wheelchair. In Freksa, C. and Habel, C., editors, *Spatial Cognition: An Interdisciplinary Approach to Representing and Processing Spatial Knowledge*, volume 1404 of *Lecture Notes in Computer Science*, pages 373–398. Springer-Verlag, Berlin.

Krueger, R., Caspi, A., Moffitt, T., Silva, P., and McGee, R. (1996). Personality traits are differentially linked to mental disorders: A multitrait–multidiagnosis study of an adolescent birth cohort. *Journal of Abnormal Psychology*, 105:299–312.

Kuipers, B. (1977). *Representing Knowledge of Large-Scale Space*. PhD thesis, Mathematics Department, Massachusetts Institute of Technology, Cambridge, MA.

Kuipers, B. (1978). Modeling spatial knowledge. *Cognitive Science*, 2(2):129–153.

Kuipers, B. (2000). The spatial semantic hierarchy. *Artificial Intelligence*, 119:191–233.

Kules, B. (2000). User modeling for adaptive and adaptable software systems. URL: `http://www.otal.umd.edu/UUGuide/wmk` (version current as of October 28, 2003).

Lander, J. (2003). Numerical instability. URL: `http://www.met.rdg.ac.uk/~swslandr/Courses/MT405/node14.html` (version current as of April 03, 2003).

Langley, P. (1997). Machine learning for adaptive user interfaces. In *Proceedings of the 21st German Annual Conference on Artificial Intelligence*.

Laurel, B. (1993). *Computers as Theatre*. Addison-Wesley Longman Publishing Co., Inc, Boston, MA.

Laurendau, M. and Pinard, A. (1970). *The Development of the Concept of Space in the Child*. International Universities Press, New York, NY.

Lauria, R. (1997). Virtual reality: An empirical-metaphysical testbed. *Journal of Computer-Mediated Communication*, 3(2).

Lauria, R. (2000). Presence-listserv. re: "presence" and media. URL: `http://listserv.temple.edu/archives/presence-l.html` (version current as of November 06, 2000).

Lawton, C. (1994). Gender differences in way-finding strategies: Relationship to spatial ability and spatial anxiety. *Sex Roles*, 30:765–779.

Lee, C. and Heuveln, B. V. (1998). Why connectionist nets are good models. *Psycoloquy*, 9(17).

Lee, T. (1973). Psychology of living space. In Downs, R. and Stea, D., editors, *Image and Environment*, pages 87–108. Aldine Publishing Company, Chicago, IL.

Leplow, B., Höll, D., Zeng, L., and Mehdorn, M. (1998). Spatial orientation and spatial memory within a 'locomotor maze' for humans. In Freksa, C. and Habel, C., editors, *Spatial Cognition: An Interdisciplinary Approach to Representing and Processing Spatial Knowledge*, volume 1404 of *Lecture Notes in Computer Science*, pages 429–446. Springer-Verlag, Berlin.

Lessiter, J. and Freeman, J. (2001). Presence—A global media quality metric. In Fröhlich, B., Deisinger, J., and Bullinger, H., editors, *Immersive Projection Technology and Virtual Environments, Proceedings of the Eurographics Workshop.*

Lessiter, J., Keogh, J., and Davidoff, J. (2000). A cross-media presence questionnaire: The ITC sense of presence inventory. *Presence: Teleoperators and Virtual Environments*, 10(3):282–297.

Lim, I. and Thalmann, D. (2001). A key-posture extraction out of human motion data. In *Proceedings of IEEE International Conference of the Engineering in Medicine and Biology Society*, pages 1167–1169.

Lin, H., Choong, Y., and Salvendy, G. (1997). Proposed index of usability: A method for comparing the relative usability of different software systems. *Behaviour and Information Technology*, 16(4–5):267–278.

Lint, H. V., Hoogendoorn, S., and Zuylen, H. V. (2002). Freeway travel time prediction with state-space neural networks. Technical Report 02-2797, Transportation Research Board.

Liu, T., Bahl, P., and Chlamtac, I. (1998). Mobility modeling, location tracking, and trajectory prediction in wireless ATM networks. *IEEE Journal on Selected Areas in Communications*, 16(6):922–937.

Loeffler, C. and Anderson, T. (1994). *The Virtual Reality Casebook.* Van Nostrand Reinhold, New York, NY.

Lombard, M. (2002). Resources for the study of presence: Presence explication. URL: http://www.temple.edu/mmc/ispr/explicat.htm (version current as of March 15, 2002).

Lombard, M. (2003). Resources for the study of presence: How do we measure presence? URL: `http://www.temple.edu/ispr/measure.htm` (version current as of September 28, 2003).

Lombard, M. and Ditton, T. (1997). At the heart of it all: The concept of presence. *Journal of Computer—Mediated Communication*, 3(2).

Lombard, M., Ditton, T., Crane, D., Davis, B., Gil-Egui, G., Horvath, K., Rossman, J., and Park, S. (2000). Measuring presence: A literature-based approach to the development of a standardized paper-and-pencil instrument. In *Third International Workshop on Presence, Delft, The Netherlands.*

Loomis, J. (1992). Distal attribution and presence. *Presence: Teleoperators and Virtual Environments*, 1(1):113–118.

Lorr, M. (1983). *Cluster Analysis for Social Scientists.* Jossey-Bass Publishers, San Francisco, CA.

Lynch, K. (1960). *Image of the City.* MIT Press, Cambridge, MA.

Lynn, D. (1991). The application of case study evaluations. ERIC/TM Digest 71, ERIC.

MacQueen, J. (1967). Some methods for classification and analysis of multivariate observations. In *Proceedings of the 5th Berkeley Symposium on Mathematical Statistics and Probability*, pages 281–297.

Macredie, R. (1995). Human factors issues in virtual reality. In *Proceedings of Virtuality–Human Factors Issues Conference.*

Madden, J. (2001). A language of design using personality theory. In *The 3rd Annual Symposium on Systems Research in the Arts.* URL: `http://www.jcrhodes.net/Program-2001.htm` (version current as of February 10, 2003).

Mallot, H., Gillner, S., Veen, H. V., and Bülthoff, H. (1998). Behavioral experiments in spatial cognition using virtual reality. In Freksa, C. and Habel, C., editors, *Spatial Cognition: An Interdisciplinary Approach to Representing and Processing Spatial Knowledge*, volume 1404 of *Lecture Notes in Computer Science*, pages 447–468. Springer-Verlag, Berlin.

Mallot, H., Steck, S., and Loomis, J. (2002). Mechanisms of spatial cognition: Behavioural experiments in virtual environments. *Künstliche Intelligenz*, 4:24–28.

Marian, I. (2002). A biologically inspired computational model of motor control development. Master's thesis, Department of Computer Science, University College Dublin, Ireland.

Marsh, D. (1999). *Applied Geometry for Computer Graphics and CAD*. Springer-Verlag, New York, NY.

Marsh, T. and Wright, P. (1999). Co-operative evaluation of a desktop virtual reality system. In Smith, S. and Harrison, M., editors, *Proceedings of Workshop on User Centered Design and Implementation of Virtual Environments*.

Massey, A. (1999). Methodological triangulation, or how to get lost without being found out. In Massey, A. and Walford, G., editors, *Explorations in Methodology, Studies in Educational Ethnography*, volume 2, pages 183–197. JAI Press.

Maupertius, P. M. (1750). *Essai de Cosmologie*. Leyde, London.

McGee, M. (1979). Human spatial abilities: Psychometric studies and environmental, genetic, hormonal, and neurological influences. *Psychological Bulletin*, 86:889–918.

McMaster, R. (1989). The integration of simplification and smoothing algorithms in line generalization. *Cartographica*, 26(1):101–121. Monograph 40.

McMaster, R. (1990). Line generalization. In Goodchild, M. and Kemp, K., editors, *NCGIA Core Curriculum in GIS*. National Center for Geographic Information and Analysis, University of California, Santa Barbara CA.

McMaster, R. and Shea, S. (1992). *Generalisation in Digital Cartography*. The Association of American Geographers, Washington D.C.

McMillan, C., Mozer, M., and Smolensky, P. (1992). Rule induction through integrated symbolic and subsymbolic processing. In Moody, J., Hanson, S., and Lippmann, R., editors, *Advances in Neural Information Processing Systems*, pages 969–976, San Mateo, CA. Morgan Kaufmann.

Mecklenbräuker, S., Wippich, W., Wagener, M., and Saathoff, J. (1998). Spatial information and actions. In Freksa, C. and Habel, C., editors, *Spatial Cognition: An Interdisciplinary Approach to Representing and Processing Spatial Knowledge*, volume 1404 of *Lecture Notes in Computer Science*, pages 39–62. Springer-Verlag, Berlin.

Medler, D. and Dawson, M. (1998). Connectionism and cognitive theories. *Psycoloquy*, 9(11).

Meng, M. and Kak, A. (1993). Mobile robot navigation using neural networks and nonmetrical environment models. In *Proceeding of IEEE Control Systems*, pages 31–42. IEEE Computer Society Press.

Messick, S. (1976). *Individuality in Learning*. Jossey-Bass, San Francisco, CA.

Milgram, P., Takemura, H., Utsumi, A., and Kishino, F. (1994). Augmented reality: A class of displays on the reality–virtuality continuum. In *Proceedings. SPIE: Telemanipulator and Telepresence Technologies*, pages 282–292, Bellingham, Wash. Society of Photo-Optical Instrumentation Engineers.

Miller, L. (1994). In the context of the European project "Metrics for usability standards in computing" (MUSiC): A usability evaluation of the Rolls-Royce virtual reality for aero engine maintenance system. Master's thesis, University College London, London.

Minsky, M. (1980). Telepresence. *Omni*, 2:44–52.

Mitchell, T. (1997). *Machine Learning.* McGraw-Hill, New York, NY.

Montello, D. (1998). A new framework for understanding the acquisition of spatial knowledge in large-scale environments. In Eganhofer, M. and Golledge, R., editors, *Spatial and Temporal Reasoning in Geographic Information Systems*, pages 143–154. Oxford University Press, Oxford.

Montello, D. (2003). Navigation. In Shah, P. and Miyake, A., editors, *Handbook of Visuospatial Thinking.* Cambridge University Press, Cambridge.

Morgan, M., Fischhoff, B., Bostrom, A., Lave, L., and Atman, C. (1992). Communicating risk to the public: First, learn what people know and believe. *Environmental Science and Technology*, 26:2048–2056.

Morris, W., Cottrell, G., and Elman, J. (2000). A connectionist simulation of the empirical acquisition of grammatical relations. In Wermter, S. and Sun, R., editors, *Hybrid Neural Symbolic Integration*, volume 1778 of *Lecture Notes in Artificial Intelligence*, pages 175–193. Springer Verlag, Berlin.

Munro, A., Höök, K., and Benyon, D. (1999a). Footprints in the snow. In Munro, A., Höök, K., and Benyon, D., editors, *Social Navigation of Information Space*, chapter Footprints in the Snow, pages 1–14. Springer, London.

Munro, A., Höök, K., and (Eds.), D. B. (1999b). *Social Navigation of Information Space.* Springer, London.

Murphy, R. (2000). *An Introduction to AI Robotics.* MIT Press, Cambridge, MA.

Musto, A., Stein, K., Eisenkolb, A., Rofer, T., Brauer, W., and Schill, K. (2000). From motion observation to qualitative motion representation. In Freksa, C., Brauer, W., Habel, C., and Wender, K., editors, *Spatial Cognition II: Integrating Abstract Theories, Empirical Studies, Formal Methods, and Practical Applications*, Lecture Notes in Computer Science 1849, pages 115–126. Springer, Berlin.

Myers, I. and McCaulley, M. (1998). *Manual: A Guide to the Development and Use of the MBTI.* Consulting Psychologist Press, Palo Alto, CA.

Nadel, L., Thomas, K., Laurance, H., Skelton, R., Tal, T., and Jacobs, W. (1998). Human place learning in a computer generated arena. In Freksa, C. and Habel, C., editors, *Spatial Cognition: An Interdisciplinary Approach to Representing and Processing Spatial Knowledge*, volume 1404 of *Lecture Notes in Computer Science*, pages 399–428. Springer-Verlag, Berlin.

Neale, D. and Caroll, J. (1999). Multi-faceted evaluation for complex, distributed activities. In *Proceedings of CSLC: Computer Supported Cooperative Learning.*

Nehmzow, U. (1992). *Experiments in Competence Aquisition for Autonomous Mobile Robots.* PhD thesis, University of Edinburgh.

Nielsen, J. (1993). *Usability Engineering.* Academic Press, London.

Nielsen, J. (2000). *Designing Web Usability: The Practice of Simplicity.* New Riders Publishing, Indianapolis, IN.

Nijholt, A., Zwiers, J., and Dijk, B. V. (2001). Maps, agents and dialogue for exploring a virtual world. In *Proceedings 5th World Multiconference on Systemics, Cybernetics and Informatics (SCI 2001)*, pages 94–99.

Nolfi, S. and Tani, J. (1999). Extracting regularities in space and time through a cascade of prediction networks: The case of a mobile robot navigating in a structured environment. *Connection Science*, 11(2):129–152.

Norman, D. (1986). Cognitive engineering. In Norman, D. and Draper, S., editors, *User Centred System Design: New Perspectives on Human–Computer Interaction.* Lawrence Erlbaum Associates, Hillsdale, New Jersey.

Norman, M. (1983). Some observations on mental models. In Gentner, D. and Stevens, A., editors, *Mental Models.* Lawrence Erlbaum Associates.

Nunnally, J. and Bernstein, I. (1994). *Psychometric Theory.* McGraw-Hill, New York, NY.

Nwana, H., Ndumu, D., and Lee, L. (1998). ZEUS: An advanced tool-kit for engineering distributed multi-agent systems. In *Proceedings of the Practical Application of Intelligent Agents and Multi-Agent Systems*, pages 377–392, London, UK.

Nwana, H., Ndumu, D., Lee, L., and Collis, J. (1999). ZEUS: A toolkit for building distributed multi-agent systems. *Applied Artificial Intelligence Journal*, 13(1):129–185.

O'Brien, G. (1998). The role of implementation in connectionist explanation. *Psycoloquy*, 9(6).

O'Hare, G. and Abbas, S. (1995). Commitment manipulation within agent factory. In *Proceedings of Decentralised Intelligent and Multi-Agent Systems, DIMAS '95.*

O'Hare, G., Sewell, K., Murphy, A., and Delahunty, T. (2000a). An agent based approach to managing collaborative work within both a virtual environment and virtual community. In *Proceedings of the Workshop on Intelligent Agents for Computer Supported Co-Operative Work: Technologies & Risks.*

O'Hare, G., Sewell, K., Murphy, A., and Delahunty, T. (2000b). An immersive training experience. In Brusilovsky, P., Stock, O., and Strapparava, C., editors, *Lecture Notes in Computer Science*, volume 1892, pages 179–188. Springer-Verlag, Berlin.

O'Keefe, J. and Nadel, L. (1978). *The Hippocampus as a Cognitive Map.* Clarendon Press, Oxford.

Opie, J. (1998). Connectionist modelling strategies. *Psycoloquy*, 9(30).

O'Regan, J. and Noë, A. (2001). A sensorimotor account of vision and visual consciousness. *Behavioral and Brain Sciences*, 24(5):883–975.

Owens, J. and Hunter, A. (2000). Application of the self-organizing map to trajectory classification. In *Proceedings of the 3rd IEEE Workshop on Visual Surveillance*, pages 77–83.

Pask, G. (1988). Learning strategies, teaching strategies, and conceptual or learning style. In Schmeck, R., editor, *Learning Strategies and Learning Styles*, pages 83–99. Plenum Press, New York, NY.

Pearlmutter, B. (1989). Learning state space trajectories in recurrent neural networks. *Neural Computation*, 1(2):263–269.

Perales, F. (2001). Human motion analysis & synthesis using computer vision and graphics techniques. state of art and applications. In *Proceedings of the 5th World Multi-Conference on Systemics, Cybernetics and Informatics.*

Pettre, J., Simeon, T., and Laumond, J. (2002). Planning human walk in virtual environments. In *Proceedings of the 2002 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pages 3048–3053.

Piaget, J. (1954). *The Child's Construction of Reality.* Basic Books, New York, NY.

Piaget, J. and Inhelder, B. (1967). *The Child's Conception of Space.* W.W. Norton and Co. Inc., New York, NY.

Plunkett, K. and Elman, J. (1997). *A Handbook for Connectionist Simulations.* MIT, Cambridge, MA.

Podolak, I. (1998). Functional graph model of a neural network. *Transactions on Systems, Man and Cybernetics*, 28(6):876–881.

Polanyi, M. (1958). *Personal Knowledge. Towards a Post Critical Philosophy.* Routledge, London.

Polanyi, M. (1966). *The Tacit Dimension.* Doubleday and Company Inc., New York, NY.

Poslad, S., Buckle, P., and Hadingham, R. (2000). The FIPA—OS agent platform: Open source for open standards. In *Proceedings of the 5th International Conference and Exhibition on the Practical Application of Intelligent Agents and Multi-Agents*, pages 355–368.

Preece, J. (1993). *Guide to Usability, Human Factors in Computing.* The Open University, Suffolk.

Preece, J., Rogers, Y., and Sharp, H. (2002). *Interaction Design: Beyond Human–Computer Interaction.* Wiley, New York, NY.

Preece, J., Rogers, Y., Sharp, H., Benyon, D., Holland, S., and Carey, T. (1994). *Human–Computer Interaction.* Addison-Wesley, Wokingham.

Prothero, J., Hoffman, H., Parker, D., Wells, M., and Furness, T. (1995a). Foreground/Background manipulations affect presence. In *Proceedings of Human Factors and Ergonomics Society*, pages 1410–1414.

Prothero, J., Parker, D., Furness, T., and Wells, M. (1995b). Towards a robust, quantitative measure for presence. In *Proceedings of the Conference on Experimental Analysis and Measurement of Situation Awareness*, pages 359–366.

Psarrou, A. and Buxton, H. (1993). Hybrid architecture for understanding motion sequences. *Neurocomputing*, 5:221–241.

Psarrou, A. and Buxton, H. (1994). Motion analysis using recurrent neural networks. In *International Conference in Artificial Neural Networks.*

Psarrou, A., Gong, S., and Buxton, H. (1995). Modeling spatio-temporal trajectories and face signatures on partially recurrent neural networks. In *Proceedings IEEE International Conference on Neural Networks*, pages 2226–2232. IEEE Computer Society Press.

Psotka, J. and Davison, S. (1993). Cognitive factors associated with immersion in virtual environments. In *Proceedings of the Conference on Intelligent Computer-Aided Training and Virtual Environment Technology.*

Quarrick, G. (1989). *Our sweetest hours: Recreation and the mental state of absorption.* Jefferson: McFarland.

Quinlan, J. (1993). *C4.5: Programs for Machine Learning.* Morgan Kaufmann Publishers, San Mateo, CA.

Raubal, M. and Worboys, M. F. (1999). A formal model of the process of wayfinding in built environments. In Freksa, C. and Mark, D., editors, *International Conference COSIT'99*, volume 1661 of *Lecture Notes in Computer Science*. Springer Verlag, Berlin.

Ravani, B. (1991). *Telepresence for Dexterous Manipulation*. American Nuclear Society, San Francisco, CA.

Reber, A. (1993). *Implicit Learning and Tacit Knowledge: An Essay in the Cognitive Unconscious*. Oxford University Press, Oxford.

Redish, A. (1997). *Beyond the Cognitive Map: Contributions to a Computational Neuroscience Theory of Rodent Navigation*. PhD thesis, Computer Science Department, Carnegie Mellon University.

Reilly, R. (1991). There's more to connectionism than feedforward and backpropagation. *Psycoloquy*, 9(2).

Revelle, W. (2000). Individual differences. In Kazdin, A., editor, *Encyclopedia of Psychology*. Oxford University Press.

Revonsuo, A. (1995). Consciousness, dreams, and virtual realities. *Philosophical Psychology*, 8:35–58.

Revonsuo, A. (1996). Virtual reality as a metaphor of consciousness. In *Proceeding of Conference Toward a Science of Consciousness*, pages 8–13.

Riding, R. and Cheema, I. (1991). Cognitive styles. *Educational Psychology*, 11(3-4):193–213.

Riding, R. and Rayner, S. (1998). *Cognitive Styles and Learning Strategies: Understanding Style Differences in Learning and Behaviour*. David Fulton, London.

Riesbeck, C. and Schank, R. (1989). *Inside Case-Based Reasoning*. Lawrence Erlbaum, Hillsdale, N.J.

Rodrigo, T. (2002). Navigational strategies and models. *Psicológica*, 23(1):3–32.

Rothkegel, R., Wender, K., and Schumacher, S. (1998). Judging spatial relations from memory. In Freksa, C. and Habel, C., editors, *Spatial Cognition: An Interdisciplinary Approach to Representing and Processing Spatial Knowledge*, volume 1404 of *Lecture Notes in Computer Science*, pages 79–106. Springer-Verlag, Berlin.

Rowe, A., Cooke, N., Hall, E., and Halgren, T. (1996). Toward an on-line knowledge assessment methodology: Building on the relationship between knowing and doing. *Journal of Experimental Psychology: Applied*, 2(1):31–47.

Rubin, J. (1994). *Handbook of Usability Testing: How to Plan, Design, and Conduct Effective Tests*. John Wiley and Sons, New York, NY.

Ruddle, R., Payne, S., and Jones, D. (1997). Navigating buildings in "desk-top" virtual environments: Experimental investigations using extended navigational experience. *Journal of Experimental Psychology: Applied*, 3:143–159.

Ruddle, R., Payne, S., and Jones, D. (1998). Navigating large-scale desk-top virtual buildings: Effects of orientation aids and familiarity. *Presence: Teleoperators and Virtual Environments*, 7(2):179–193.

Rumelhart, D., Hinton, G., and McClelland, J. (1986). A general framework for parallel distributed processing. In Rumelhart, D. E., McClelland, J., and the PDP Research Group, editors, *Parallel Distributed Processing: Explorations in the Microstructure of Cognition*, volume 1: Foundations. MIT Press, Cambridge.

Rushton, S. and Wann, J. (1993). Problems in perception and action in virtual worlds. In *Proceedings of Virtual Reality International 93*, pages 43–55, London. Meckler.

Sadowski, W. and Stanney, K. (2002). Measuring and managing presence in virtual environments. In Stanney, K., editor, *Handbook of Virtual Environments Technology*. Lawrence Erlbaum Associates.

Sas, C., O'Grady, M., and O'Hare, G. (2003a). Electronic navigation—some design issues. In Chittaro, L., editor, *Fifth International Symposium on Human Computer Interaction with Mobile Devices and Services*, volume 2795 of *Lecture Notes in Computer Science*, pages 471–475. Springer-Verlag, Berlin.

Sas, C. and O'Hare, G. (2001). The presence equation: An investigation into cognitive factors underlying presence within non-immersive virtual environments. In *Presence 2001, The 4th Annual International Workshop on Presence*.

Sas, C. and O'Hare, G. (2002). Presence and individual differences in virtual environment: Usability study. In Sharp, H., Chalk, P., LePeuple, J., and Rosbottom, J., editors, *Proceedings of 16th British HCI Conference*, volume 2, pages 50–53, London. British Computer Society.

Sas, C. and O'Hare, G. (2003). Presence equation: An investigation into cognitive factor underlying presence. *Presence: Teleoperators and Virtual Environments*, 12(5):523–537.

Sas, C., O'Hare, G., and Reilly, R. (2002). A connectionist approach to modelling navigation: Trajectory self organization and prediction. In Carbonell, N. and Stephanidis, C., editors, *Proceedings of 7th ERCIM Workshop, User Interfaces for All*, pages 111–116.

Sas, C., O'Hare, G., and Reilly, R. (2003b). A connectionist model of human navigation. In *Proceedings of the 7th International Conference on Cognitive and Neural Systems*, page 89, Boston, MA. Boston University Press.

Sas, C., O'Hare, G., and Reilly, R. (2003c). On-line trajectory classification. In *Lecture Notes in Computer Science 2659*, pages 1035–1044. Springer-Verlag, Berlin.

Sas, C., O'Hare, G., and Reilly, R. (2004a). A performance analysis of movement patterns. In *Lecture Notes in Computer Science*. Springer-Verlag, Berlin. In press.

Sas, C., O'Hare, G., and Reilly, R. (2004b). Virtual environment trajectory analysis: A basis for navigational assistance and scene adaptivity. *Future Generation Computer Systems. Special Issue on "Interaction and Visualisation Techniques for Problem Solving Environments"*. In press.

Sas, C., Reilly, R., and O'Hare, G. (2001). *Virtual Reality. Cognitive Foundations, Technological Issues, and Philosophical Implications*, chapter Virtual Reality in Surgery: Between Satisfaction and Stress, pages 99–111. Peter Lang Verlag, Frankfurt.

Sasse, M. (1991). How to t(r)ap users' mental models. In Tauber, M. and Ackermann, D., editors, *Mental Models and Human–Computer Interaction*, pages 59–80. Elsevier Science Publishers, Amsterdam.

Satalich, G. (1995). Navigation and wayfinding in VR: Finding the proper tools and cues to enhance navigational awareness. Master's thesis, Department of Computer Science, University of Washington.

Savidis, A., Paramythis, A., Akoumianakis, D., and Stephanidis, C. (1997). Designing user-adapted interfaces: The unified design method for transformable interactions. In *ACM Conference on Designing Interactive System: Processes, Methods and Techniques*, pages 323–334.

Sayers, H., Wilson, S., Myles, W., and McNeill, M. (2000). Usable interfaces for virtual environment applications on non-immerse systems. In *Proceedings Eurographics*, pages 143–150.

Schloerb, D. and Sheridan, T. (1995). Experimental investigation of the relationship between subjective telepresence and performance in hand-eye tasks. In *Telemanipulator and Telepresence Technologies*, pages 62–73, Bellingham. Society of Photo-optical Instrumentation Engineers.

Schmid, U. (1998). Bottom-up and top-down processes in learning. *Psycoloquy*, 9(76).

Schubert, T., Friedmann, F., and Regenbrecht, H. (1999). Decomposing the sense of presence: Factor analytic insights. In *The 2nd International Workshop on Presence, University of Essex.*

Shao, L. and Zhou, H. (1996). Curve fitting with bézier cubics. *Graphical Models and Image Processing*, 58(3):223–232.

Shapiro, M. and McDonald, D. (1993). I'm not a doctor, but I play one in virtual reality. *Journal of Communication*, 42(4):94–114.

Shemyakin, F. (1962). Psychological science in the USSR. Technical Report 62-11083, Office of Technical Services, Washington. Cited in Hart, R. A. and Moore, G., 1973, The Development of Spatial Cognition: A Review, in R. M. Downs and D. Stea (eds.), Image and Environment, pp. 246–288, Chicago, Aldine Publishing Company.

Sheridan, T. (1992). Musings on telepresence and virtual presence. *Presence: Teleoperators and Virtual Environments*, 1(1):120–126.

Shimrat, M. (1962). Algorithm 112: Position of point relative to polygon. *Communications of the ACM*, 5(8):434.

Shneiderman, B. (2000). Universal usability: Pushing human–computer interaction research to empower every citizen. *Communications of the ACM*, 43(5):84–91.

Shoham, Y. (1993). Agent oriented programming. *Artificial Intelligence*, 60(1):51–92.

Siegel, A. and White, S. (1975). The development of spatial representations of large-scale environments. In Reese, H., editor, *Advances in Child Development and Behavior*, volume 10, pages 9–55. Academic Press, New York, NY.

Singer, J. (2000). Imagination. In Kazdin, A., editor, *Encyclopedia of Psychology*, volume 4, pages 227–230. Oxford University Press, Oxford.

Singh, G. and Feiner, S. (1995). Introduction to the special issue on virtual reality. *Transactions on Computer–Human Interaction, Special Issue on Virtual Reality Software and Technology*, 2:177–178.

Sjölinder, M. (1998). Spatial cognition and environmental descriptions. In Dahlbäck, N., editor, *Exploring Navigation: Towards a Framework for Design and Evaluation of Navigation in Electronic Spaces*. Swedish Institute of Computer Science.

Slater, M., Linakis, V., Usoh, M., and Kooper, R. (1996). Immersion, presence and performance in virtual environments: An experiment with tri-dimensional chess. In Green, M., editor, *Virtual Reality Software and Technology*, pages 163–172. ACM Press.

Slater, M. and Steed, A. (2000). A virtual presence counter. *Presence: Teleoperators and Virtual Environments*, 9(5):413–434.

Slater, M., Steed, A., and Usoh, M. (1993). The virtual treadmill: A naturalistic method for navigation in immersive virtual environments. In *Immersive Virtual Environments, First Eurographics Workshop on Virtual Environments*, pages 71–83.

Slater, M. and Usoh, M. (1993a). An experimental exploration of presence in virtual environments. Technical Report 689, Department of Computer Science, QMW University of London.

Slater, M. and Usoh, M. (1993b). Representations systems, perceptual position, and presence in immersive virtual environments. *Presence: Teleoperators and Virtual Environments*, 2(3):221–233.

Slater, M. and Usoh, M. (1995). Modelling in immersive virtual environments: a case for the science of VR. In Earnshaw, R., Vince, J., and Jones, H., editors, *Virtual Reality Applications*. Academic Press, London.

Slater, M., Usoh, M., and Steed, A. (1995). Taking steps: The influence of a walking metaphor on presence in virtual reality. *ACM Transactions on Computer–Human Interaction (TOCHI)*, 2(3):201–219.

Slusarz, P. and Sun, R. (2001). The interaction of explicit and implicit learning: An integrated model. In *Proceedings of the 23rd Cognitive Science Society Conference*, pages 952–957, Mahwah, NJ. Lawrence Erlbaum Associates.

Smith, T. and Smith, K. (1985). Cybernetic factors in motor performance and development. In Goodman, D., Wilberg, R., and Franks, I., editors, *Differing Perspectives in Motor Learning, Memory, and Control*, pages 239–283. Elsevier Science Publishers.

Smolensky, P. (1987). The constituent structure of connectionist mental states: A reply to Fodor and Pylyshyn. Technical Report CU-CS-377-87, Department of Computer Science, University of Colorado.

Snow, M. (1996). *Charting Presence in Virtual Environments and Its Effects on Performance.* PhD thesis, Industrial and Systems Engineering, Virginia Polytechnic Institute and State University.

Stanney, K. (1995). Realizing the full potential of virtual reality: Human factors issues that could stand in the way. In *Proceedings of IEEE Virtual Reality Annual International Symposium*, pages 28–34. IEEE Computer Society Press.

Stanney, K., Mourant, R., and Kennedy, R. (1998a). Human factors issues in virtual environments: A review of the literature. *Presence: Teleoperators and Virtual Environments*, 7(4):327–351.

Stanney, K. and Salvendy, G. (1995). Information visualization: Assisting low spatial individuals with information access tasks through the use of visual mediators. *Ergonomics*, 38(6):1184–1198.

Stanney, K., Salvendy, G., Deisigner, J., DiZio, P., Ellis, S., Ellison, E., Fogleman, G., Gallimore, J., Hettinger, L., Kennedy, R., Lackner, J., Lawson, B., Maida, J., Mead, A., Mon-Williams, M., Newman, D., Piantanida, T., Reeves, L., Riedel, O., Singer, M., Stoffregen, T., Wann, J., Welch, R., Wilson, J., and Witmer, B. (1998b). Aftereffects and sense of presence in virtual environments: Formulation of a research and development agenda. *International Journal of Human–Computer Interaction*, 10(2):135–187.

Stea, D. and Blaut, J. (1973). Toward a developmental theory of spatial learning. In Downs, R. and Stea, D., editors, *Image and Environment*, pages 51–78. Aldine Publishing Company, Chicago, IL.

Steuer, J. (1992). Defining virtual reality: Dimensions determining telepresence. *Journal of Communication*, 4(2):73–93.

Strohecker, C., Barros, B., and Slaughter, A. (1998). Mapping psychological and virtual spaces. Technical Report TR98-12, Mitsubishi Electric Research Laboratories.

Sudarsky, S. and House., D. (1998). *Motion capture data manipulation and reuse via B-splines*, volume 1537 of *Lecture Notes in Artificial Intelligence*, pages 55–69. Springer-Verlag, Berlin.

Sühling, M., Arigovindan, M., Hunziker, P., and Unser, M. (2002). Motion analysis of echocardiograms using a local-affine, spatio-temporal model. In *Proceedings of the IEEE International Symposium on Biomedical Imaging: Macro to Nano*, pages 573–576.

Sun, R. and Zhang, X. (2002). Top–down versus bottom–up learning in skill acquisition. In *Proceedings of the 24th Annual Conference of the Cognitive Science Society*.

Sundareshan, M., Wong, Y., and Condarcure, T. (1999). Training algorithms for recurrent neural nets that eliminate the need for computation of error gradients with application to trajectory production problem. In Medsker, L. and Jain, L., editors, *Recurrent Neural Networks: Design and Applications*, pages 277–323. CRC Press, Boca Raton.

Suwa, M. and Tversky, B. (2002). External representations contribute to the dynamic construction of ideas. In Hegarty, M., Meyer, B., and Narayanan, N., editors, *Diagrammatic Representation and Inference, Proceedings of Diagrams 2002*, Lecture Notes in Artificial Intelligence, pages 341–343. Springer Verlag, Berlin.

Taube, J., Muller, R., and Ranck, J. (1990). Head direction cells recorded from the postsubiculum in freely moving rats. I description and quantitative analysis. *Journal of Neuroscience*, 10:420–435.

Tellegen, A. (1981). Practicing the two disciplines of relaxation and enlightenment: Comment on “Role of the feedback signal in electromyography biofeedback: The relevance of attention” by Qualls and Sheehan. *Journal of Experimental Psychology: General*, 110:217–226.

Tellegen, A. (1982). Brief manual for the differential personality questionnaire. Unpublished manuscript. Department of Psychology, University of Minnesota, Minneapolis.

Tellegen, A. and Atkinson, G. (1974). Openness to absorbing and self-altering experiences ("Absorption"), a trait related to hypnotic susceptibility. *Journal of Abnormal Psychology*, 83:268–277.

Terrazas, A. and McNaughton, B. (2000). Commentary brain growth and the cognitive map. *Proceedings of the National Academy of Science of the United States of America*, 97(9):4414–4416.

Thorndyke, P. and Hayes-Roth, B. (1982). Differences in spatial knowledge acquired from maps and navigation. *Cognitive Psychology*, 14:560–589.

Tolman, E. (1948). Cogintive map in man and animals. *Psychological Review*, 55:189–208.

Trochim, W. (2000). *The Research Methods Knowledge Base.* URL: `http://trochim.human.cornell.edu/kb/index.htm` (version current as of August 02, 2000).

Tromp, J. (1995). Presence, telepresence and immersion: The cognitive factors of embodiment and interaction in virtual environments. In *Proceedings of Immersive Virtual Environments.*

Tromp, J. (1997). Methodology of distributed CVE evaluations. In *Proceedings of UK VR SIG.*

Tryan, M. (2001). Some example applications of augmented reality and the technical issues to be solved. Invited talk to SLIS Colloquium, Indiana University, School of Library and Information Science.

Tuan, Y. (1975). Images and mental maps. *Annals, Association of American Geographers*, 65(2):205–213.

Turban, E. and Aronson, J. (1998). *Decision Support System and Intelligent Systems.* Prentice Hall, Upper Saddle River, NJ.

Tversky, B. (1991). Spatial mental models. In Bower, G., editor, *The Psychology of Learning and Motivation: Advances in Research and Theory*, volume 27, pages 109–145. Academic Press, New York, NY.

Tversky, B. (1993). Spatial information theory: A theoretical basis for GIS, proceedings COSIT'93. In Frank, A. and Campari, I., editors, *Lecture Notes in Computer Science*, volume 716, chapter Cognitive Maps, Cognitive Collages, and Spatial Mental Models, pages 14–24. Springer-Verlag, Berlin.

Tversky, B. and Lee, P. (1999). Pictorial and verbal tools for conveying routes. In Freksa, C. and Mark, D., editors, *International Conference COSIT'99*, volume 1661 of *Lecture Notes in Computer Science*. Springer Verlag, Berlin.

Unadkat, S., Ciocoiu, M., and Medsker, L. (1999). Introduction. In Medsker, L. and Jain, L., editors, *Recurrent Neural Networks: Design and Applications*, pages 1–12. CRC Press, Boca Raton.

Ungar, S. (2003). Comparative spatial cognition. URL: `http://www.lgu.ac.uk/psychology/ungar/lecturenotes/compsp/compsp.doc` (version current as of November 25, 2003).

Utgoff, P. (1989). Incremental induction of decision trees. *Machine Learning*, 4(2):161–186.

Vaccaro, A. (1988). Personality clash. *Personnel Administrator*, pages 88–92.

Vinson, N. (1999). Design guidelines for landmarks to support navigation in virtual environments. In *Proceedings of CHI '99*, pages 278–285. ACM Press.

Volbracht, V. and Domik, G. (2000). Developing effective navigation techniques in virtual 3D environments. In *Proceedings of the Eurographics Workshop*, pages 55–64, Berlin. Springer-Verlag.

Wahlström, B. (1988). On the use of models in human decision making. In Goodstein, L., Andersen, H., and Olsen, S., editors, *Tasks, Errors and Mental Models*, pages 160–170. Taylor and Francis, London.

Waller, D. (2000). Individual differences in spatial learning from computer—simulated environments. *Journal of Experimental Psychology: Applied*, 8:307–321.

Waller, D., Hunt, E., and Knapp, D. (1998). The transfer of spatial knowledge in virtual environment training. *Presence: Teleoperators and Virtual Environments*, 7(2):129–143.

Waller, D., Knapp, D., and Hunt, E. (2001). Spatial representations of virtual mazes: The role of visual fidelity and individual differences. *Human Factors*, 43:147–158.

Waller, D. and Miller, J. (1998). A desktop virtual environment trainer provides superior retention of a spatial assembly skill. In *Proceeding of ACM SIGCHI 98 (Poster)*.

Warner, R. (1998). *Spectral Analysis of Time-Series Data*. The Guilford Press, London.

Warnett, L. and McGonigle, B. (2002). Unsupervised navigation using an economy principle. In Prince, C. G., Demiris, Y., Marom, Y., Kozima, H., and Balkenius, C., editors, *Proceedings of the Second International Workshop on Epigenetic Robotics: Modeling Cognitive Development in Robotic Systems*.

Wartenberg, F., May, M., and Péruch, P. (1998). Spatial orientation in virtual environments: Background considerations and experiments. In Freksa, C. and Habel, C., editors, *Spatial Cognition: An Interdisciplinary Approach to Representing and Processing Spatial Knowledge*, volume 1404 of *Lecture Notes in Computer Science*, pages 469–489. Springer-Verlag, Berlin.

Webb, E., Campbell, D., Schwartz, R., Sechrest, L., and Grove, J. (1966). *Nonreactive Measures in the Social Sciences*. Rand McNally, Chicago, IL.

Webb, G., Pazzani, M., and Billsus, D. (2001). Machine learning for user modeling. *User Modeling and User-Adapted Interaction*, 11:19–29.

Weiman, H. (2003). Gender differences in cognitive functioning. URL: `http://homepages.luc.edu/~hweiman/GenderDifferences.html` (version current as of November 17 2003).

Weisman, J. (1981). Evaluating architectural legibility: Way-finding in the built environment. *Environment and Behavior*, 13:189–204.

Weisstein, E. W. (2003). Curvature. URL: `http://mathworld.wolfram.com/Curvature.html` (version current as of May 10, 2003). Wolfram Research, Inc.

Welch, R., Blackmon, T., Liu, A., Mellers, B., and Stark, L. (1996). The effects of pictorial realism, delay of visual feedback, and observer interactivity on the subjective sense of presence. *Presence: Teleoperators and Virtual Environments*, 5(3):263–273.

Weld, D. (1995). The role of intelligent systems in the national information infrastructure. *AI Magazine*, pages 45–64.

Werner, S., Saade, C., and Lüer, G. (1998). Relations between the mental representation of extrapersonal space and spatial behavior. In Freksa, C. and Habel, C., editors, *Spatial Cognition: An Interdisciplinary Approach to Representing and Processing Spatial Knowledge*, volume 1404 of *Lecture Notes in Computer Science*, pages 107–128. Springer-Verlag, Berlin.

Winn, J. (2003). Psychological basis for instruction. URL: `http://www.sph.uth.tmc.edu/causes/CHP/ph1110/basis.htm` (version current as of October 02, 2003).

Witkin, H. and Goodenough, D. (1981). *Cognitive Styles: Essence and Origins: Field Dependence and Independence*. International Universities Press, Inc, New York, NY.

Witmer, B., Bailey, J., and Knerr, B. (1995). Training dismounted soldiers in virtual environments: Route learning and transfer. Technical Report 1022, U.S. Army Research Institute for the Behavioral and Social Sciences.

Witmer, B. and Singer, M. (1994). Measuring immersion in virtual environments. Technical Report 1014, Army Research Institute for the Behavioral and Social Sciences, Alexandria, VA.

Witmer, B. and Singer, M. (1998). Measuring presence in virtual environments: A presence questionnaire. *Presence: Teleoperators and Virtual Environments*, 7(3):225–240.

Wloka, D. (1996). CAVE: Personal or small group non-HMD-based head tracked wrap-around virtual environment — the system of the future for virtual reality applications? In *Virtual Reality World 96 Conference Proceedings*, Stuttgart, Germany.

Young, R. (1983). Surrogates and mappings: Two kinds of conceptual models for interactive devices. In Gentner, D. and Stevens, A., editors, *Mental Models*, pages 35–52. Lawrence Erlbaum Associates, Hillsdale, NJ.

Zell, A., Mamier, G., Vogt, M., Mache, N., Hubner, R., Doring, S., Herrmann, K., Soyez, T., Schmalzl, T., Sommer, T., Hatzigeorgiou, A., Posselt, D., Schreiner, T., Kett, B., Clemente, G., and Wieland, J. (1995). *The SNNS Users Manual Version 4.1.* Institute for Parallel and Distributed High Performance Systems. URL: `http://www.informatik.uni-stuttgart.de/ipvr/bv/projekte/snns/UserManual%/UserManual.html` (version current as of 4th July 2002).

Zeltzer, D. (1992). Autonomy, interaction and presence. *Presence: Teleoperators and Virtual Environments*, 1(1):127–132.

Zhang, J. (1997). The nature of external representations in problem solving. *Cognitive Science*, 21(2):179–217.

Zhang, X. and Li, Y. (1998). Efficient evaluation of binomial coefficients and applications. In Coleman, T., editor, *Conference Proceedings NASA University Research Center*, pages 376–381, Albuquerque, NM. ACE Center Press.

Appendix A

Instructions

Welcome to the Practice and Research in Intelligent Systems and Media (PRISM) Laboratory. Thank you for your participation in this study, whose primary goal is to assess a virtual reality system. Your anonymity will be preserved, though some factual data will be required for statistical purposes. Please note that this experiment will be recorded by video.

Please feel free to ask any questions to enable better understanding of the tasks.

1. In the beginning you will be introduced to a virtual reality environment, consisting of a multi-storey building.
2. Furthermore you will be asked to perform some tasks in the virtual environment. Try to carry them out precisely, accurately, and as quickly as possible. Feel free to think aloud. You can't go through the objects, so try to avoid bumping into them!
3. Subsequently you will be taken out of the virtual space and you will be asked to fill in questionnaires regarding your level of participation in the previous tasks.
4. After this you will be asked to undertake another task. You will get detailed instructions for this in due course.
5. You will then be asked to complete some questionnaires. One is related to system usability and while others will try to capture some psychological dimensions associated with your level of participation.

We hope you will enjoy this experience and thank you for your time and willingness to help us!

Imagine that you are following a thief who managed to steal a very valuable Van Gogh painting. He is hiding now inside a new multi-storey building, which is not completely furbished and where people are not working yet. Your task is to find the painting and catch the thief. You have only 20 minutes for this action.

This is the last image of the painting on the museum wall.

Appendix B

User Satisfaction Questionnaire

Please rate the next issues, regarding your satisfaction with this 3D virtual reality system. The score meaning is as follows: *not at all* = 1, *to a very small extent* = 2, *to a small extent* = 3, *just right* = 4, *to a great extent* = 5, *to a very great extent* = 6 and *completely* = 7.

	Item	1	2	3	4	5	6	7
1.	To what extent were you frustrated with the system?							
2.	How satisfied are you with the shape of the rooms?							
3.	How satisfied are you with the height of the rooms?							
4.	To what extent do some rooms contain too less objects?							
5.	How satisfied are you with the 3D perspective?							
6.	To what extent is the cursor's movement synchronised with mouse movement/arows keys?							
7.	How satisfied are you with the ease of right-handed movement?							
8.	How satisfied are you with the ease of left-handed movement?							
9.	How satisfied are you with the ease of moving forward?							
10.	How satisfied are you with the ease of moving in reverse?							
11.	How satisfied are you with the ease of rotating?							

List the strengths of the system:
....
....

List the weaknesses of the system:
....
....

List some proposals for optimising the system:
....
....

Appendix C

Presence Questionnaire

Please rate the next issues, regarding your experience within the virtual environment. The score meaning is as follows: *not at all* = 1, *to a very small extent* = 2, *to a small extent* = 3, *just right* = 4, *to a great extent* = 5, *to a very great extent* = 6 and *completely* = 7.

	Item	1	2	3	4	5	6	7
1.	To what extent did you feel that another world existed there?							
2.	To what extent did you feel as if you were entering the other world?							
3.	To what extent were you aware of being just in front of a desktopand not inside the virtual world?							
4.	To what extent did you feel as if you were no longer in the real world?							
5.	To what extent did you feel as if you were there?							
6.	To what extent were you aware of being there, inside the virtual building?							
7.	To what extent did you feel that you were not permanently present in the real world?							
8.	To what extent did you perceive yourself as being immersed in the virtual world?							
9.	To what extent did you perceive the stimuli fromthe remote environment as if they were real?							
10.	To what extent were you be able to imagine that world as if it was real?							

	Item	**1**	**2**	**3**	**4**	**5**	**6**	**7**
11.	**To what extent were your mental resources focused there?**							
12.	**To what extent did you act within the virtual world as if you would do it in the real one?**							
13.	**To what extent did you perceive the virtual world as surrounding you?**							
14.	**To what extent did you really feel yourself navigating within another world?**							
15.	**To what extent did you feel as the results of your interactions with the remote environment can “touch” you?**							
16.	**To what extent was your attention focused there?**							
17.	**To what extent did you perceive the desktop as a window to the virtual world?**							
18.	**To what extent did you feel the real world as distant?**							
19.	**To what extent would you fail to recall things that happened in the real world during experiment?**							
20.	**To what extent did your real actions consist only in the interaction with the remote world?**							
21.	**When the experiment ended, to what extent did you feel as returning from somewhere else?**							
22.	**To what extent did you perceive the virtual world as images just in front of you?**							