Space Syntax and Human Cognitive Representations

The structures that underlie maps

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To dear Papa
(1945-2004)

Abstract

Space Syntax methodology has used a topological representation of space to provide robust correlations with aggregate movement at the urban scale. There has been a long-standing debate about whether this is due to *network effects* - i.e., the mathematical distribution of movement throughout the spatial network – or whether correlations between formal measures of the spatial structure and aggregate movement imply a cognitive response to the spatial attributes at a generic level. However, recent research shows a differentiation in the degree to which the three factors - fewest turns, least angular deviations, and least distance - have an impact upon aggregate movement, and therefore strongly suggests the involvement of a human cognitive factor in movement.

This paper evaluates the cognitive implications of modelling space using Space Syntax methodologies, which contradict traditional methods of assessing human route choice and preference. Assessing these implications against relevant cognitive literature, this paper attempts to understand how far landmarks, linearity, and the topological, geometrical and metrical properties of space play a role in spatial cognition by the *generic human being*. A model for the 'Human Cognitive Representation of Space' [HCRS] is then proposed, taking into account the way in which the generic human being understands space, 'information in space', and 'information about space', and how the HCRS acts as a filter between the two. It is expected that such a comparison will shed light not only upon the way Space Syntax models space, but also upon the approach towards human space in cognitive geography and the cognitive and behavioural sciences.

Keywords: Space Syntax; Spatial Cognition; Human Cognitive Representation of Space [HCRS]; Human Cognitive Process; Human Generic Cognitive Function

Contents

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Glossary

Animat - Virtual being or robot in a CPM

CPM - Computation Process Model

HCRS - Human Cognitive Representation of Space

LTM - Long Term Memory

NNH - Nearest Neighbour Heuristic

SSH - Spatial Semantic Hierarchy

WM - Working Memory

Introduction

Space Syntax is a theory of the built environment which seeks to inform design through spatial analysis and an understanding of the functional needs of society. It is based on the realisation that, in the built environments that we navigate through, the aggregation of forms provides the basis for the formation of useable open space. This open space links all the built forms together and provides opportunities for action. Hence, "the form and shape of the open space system ... constitute our experience" [Hillier and Hanson 1984: 89][1]. Space Syntax further employs certain representations of space in order to enable formal analysis of useable space. In this sense, the space syntax theory is not only an intellectual field but also a tool for formal spatial analysis.

The underlying spatial structure is derived from simplified representations of space that are used to calculate 'depth', i.e., the number of 'steps' required to traverse from one spatial element in the system to another[2,3]. Hence, using simple mathematical formulae, a measure of accessibility to all other spaces in the grid is defined; wherein the space that is least deep in the entire system is the most accessible from all other spaces and hence the most "integrated" [Hillier and Hanson 1984]. Human behaviour has been found to correlate well with these formal measures of the underlying spatial structure. The observed relationship between aggregate human behaviour and spatial structure, and in particular the correlation between integration and the number of occupants of a space, has raised questions about whether space syntax somehow models the way we understand space, thus aligning space syntax to the field of spatial cognition.

However, the idea of *human comprehension of space* in space syntax arises from the space syntax measure of "intelligibility"[4], Experiments conducted on people in immersive virtual environments have shown that wayfinding ability is greatly improved in more intelligible environments, while in less

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[1] See [Hillier & Hanson 1984: 85-88; Hillier 1996: 275-334] for combinatorial restrictions in spatial layouts; [Hillier & Hanson 1984: 52-61] for a discussion on the random restricted process

[2] For a brief overview of space syntax representations: see Appendix 1

[3] The software used to calculate these measures include: NetBox, Axman, WebMap, Pesh, DepthMap, etc. The software used depends upon the methodology adopted.

[4] Intelligibility is the correlation obtained between the integration values and connectivity of spaces in a system [Hillier & Hanson 1984]. Hence, intelligibility tends to be higher for a system where the more integrated (shallower) lines in the system are also the more connected, while the less integrated lines (those located deeper in the system) are the less connected.

intelligible environments people tend to wander all over the system in finding their way from one point to another [Conroy-Dalton 2001, 2003]. In a study of Hampstead Garden Suburb, integration values obtained by axial analysis of sketch maps drawn by residents correlate strongly with actual values, though the sketch maps were distorted and partial [Kim 1999, Kim & Penn 2004][5]. Recent studies of segment-based axial models of urban areas in London analysed separately for fewest turns, least angular change, and least metric distance [Hillier 2004; Iida & Hillier 2005] have consistently found better correlations with movement for the former two variables than the latter. These studies strongly imply the presence of a human cognitive factor in movement, and one that is possibly reflected in the methods adopted by space syntax in modelling space. Hence, it might be asked:

How does space as modelled using space syntax techniques relate to "the shape of cognitive space"[6]? Further:

What can we then say about the way we process information about space?

The aim of this thesis is to analyse how the findings of various cognitive sciences have a bearing on the way in which space syntax characterizes space, which has proved effective in understanding aggregate human movement and, to some extent, behavioural patterns and stationary activity. It is expected that such a comparison would allow an insight into what steps could be taken next in the field of the cognitive sciences in order to better our understanding of the human cognitive representation of space [HCRS][7,8].

Specific Research Questions:

It has been suggested above that the correlations between space syntax representations and movement imply that these representations somehow also model the way we perceive/cognise space. However, these representations exclude most information popularly considered essential in

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[5] These and other relevant studies are discussed in more detail during the course of this study

[6] Penn 2001: 54

[7] The term ***human cognitive 'representation' of space*** has been purposefully adopted in this study in order to prevent comparisons to geographical representations of space and subsequent biases towards map-like, route-like, configurational, or other types of representations; for a discussion see Chapter 2.

[8] According to Hillier [2004], aggregate movement is a result of decisions made inside the heads of individuals; it is therefore possible to stipulate the presence of a *generic human cognitive subject*. Since the pattern of movement has been seen to vary with certain spatial characteristics, it might be enquired whether space syntax methodologies can tell us something about the *generic cognitive representation*.

modelling human spatial experience, spatial navigation, and movement on the large scale. Hence, it is evident that space syntax methods of modelling space hardly follow any cartographic norms. Suggesting that a representation bare of such supposedly *essential* information corresponds in some way to our cognitive model(s) of space, has some theoretical implications.

First, the representations put forward by space syntax are devoid of information popularly considered essential to the human comprehension of space. The lack of information from landmarks and sensory cues is one of the primary criticisms of space syntax methodology. However, referring to the robust correlations that are nevertheless obtained from representations devoid of such information, it might be asked: **how far do we represent space independently of visual markers such as landmarks and signage?** This argument will consider theories in human wayfinding and navigation, and attempt to enquire how a landmark-based cognitive representation would also meet the needs of cognitive efficiency.

Second, the use of the fewest-line axial map by space syntax seems to imply a linear representation of space on a large scale. While an approximation of the line matrix of the entire system has proven to be an appropriate model on mathematical grounds, it might be asked whether it also tells us how we build an overall picture of the system. **In other words, how far is linearity inherent in the way human beings model space in their minds?** This section of the thesis will look into the existing evidence from the cognitive sciences, and evaluate explicitly what this says about linearity in cognitive space. This argument will then be tied with the previous argument to gain further insight into the structure of our cognitive map.

The third argument will deal with the graphical representation of space adopted by Space Syntax methodology. This representation is not a true map of the space but one in which the configurationality of the spatial network is considered to be of the most importance. The different correlations obtained with the metric versus the topological and geometric properties of space raise the question: **to what degree do the topological, geometric, and metric properties of space play a role in our mental representation of space?** This section of the thesis will evaluate whether our mental representations are as independent of metric information as space syntax suggests them to be. In addition, the reliance on topological and geometric information for navigation will be compared in order to derive information about the structure of the human cognitive representation.

The paper will first briefly overview the various strands of research in environmental cognition, and attempt to clarify the role of space syntax in this field. The individual research questions will then be taken up in separate chapters, and the relevant research will be discussed in more detail within each chapter, at the end of which the ideas from the chapter will be summarised. The findings will then be summed up in the section on discussion, and relevance to further research outlined.

Research Methodology, Limitations, and Structure

Due to its limited scope, this study has been conducted purely on a theoretical level. Arguments from various braches of spatial cognition have been presented, including relevant experimental work, theories and other literature. However, it must be noted that this is not a random collection of ideas from this field. This is a collection of viewpoints organised according to the three specific research questions set out above. First, the bringing together of different viewpoints under one specific question clarifies why the viewpoints are different in the first place, and this will become apparent during the course of this paper. Second, the aim of bringing these viewpoints together is to propose a model for the interaction of the spatial and cognitive processes, and the way in which the HCRS presents a filter between the two. Third, it is because a model has to be proposed that an answer to each specific research question will be attempted. However, it might be noted that these arguments (and therefore the model proposed) only consider the *generic human being*, and might not in all cases apply to individual wayfinding and behaviour.

The first chapter sets out the background to this study. It first outlines the role of space syntax in understanding environmental complexity. This is followed by an overview of the prominent strands of research into environmental cognition, which also outlines the contribution of this study to the same.

The second chapter deals with the role of landmarks in the HCRS. In order to do so, this chapter first assesses the form of the cognitive representation; it then evaluates how far such a representation can rely upon landmark knowledge. It is argued that, while landmarks might play a role in executing a predetermined sequence of moves, they can form the basis for neither an integrated representation of space, nor a configurational one. Landmark knowledge is thereby equated to 'information in space', which forms a subordinate layer in the cognitive representation.

The third chapter assesses how far the HCRS relies on linearity, arguing that linearity is a tool to counter the complexity of the environment. It is argued that the schematic linearization and chunking together of routes aids efficient retrieval of information. This is followed by an assessment of the way in which linear encoding meets the demands of accuracy while also maintaining informational efficiency.

The previous two chapters form the basis for further evaluating the graph-like representation of space in the fourth chapter. It will be suggested that fuzzy qualitative information is processed with the aid of certain heuristics in order to obtain distance and direction estimates at various scales. This chapter will argue that it is the reliance of the HCRS on topology and geometry that leads to errors in the estimation of metric distance and (to some extent) direction. The role of topology and geometry in integrating information will also be clarified.

The fifth chapter ties together the arguments presented in this paper, proposing a model for the human generic cognitive function. It is suggested that the HCRS relies upon three things: topological 'information about space', 'information in the head' (the semantic pattern of schematised geometry which aids spatial understanding at a global scale), and the process of hierarchical retrieval of spatial descriptions. This will help clarify directions for further research.

Chapter 1: Setting the context

> ***"To act effectively in space, people need mental representations of space"*** *[Tversky, 2003]*
>
> ***"Spatial Cognition refers to those mental structures and processes which allow an individual to think; imagine, interact with, and communicate about space"*** *[Medyckyj-Scott & Blades, 1992]*

The Spatial Syntax of Complex Spaces & Environmental Cognition

It is widely accepted that we store information about our surroundings in mental constructs similar to maps[9] [Kuipers 1982, Tversky 1993, Hirtle 1998], which are essential to navigation in complex environments. By definition, a complex environment is one that is non-homogeneous with respect to the phenomena being studied [Nicolis G & Prigogine I, 1989], and therefore contains uniform or non-uniform patterns of *change* [10], that can be experienced by an observer moving from point A to point B within the environment [ibid.]. Hillier (2003) presents a case of complexity in the arrangement of numbers, wherein the sequence of numbers reducible to the least and simplest rules is the least complex. Deriving from Hillier (1996; 1999; 2003), it might be suggested that the more non-uniform the changes, the more complex the environment in question. In spatial terms, complexity implies two things:

- All spaces within the environment are not perceptible to the senses from a single point; and
- Relations between the different spaces within the environment are non-identical.

Hillier (2004) suggests that a single *convex*[11] space is a simple environment while multiple spaces - wherein many simple spaces must be linked together to form an overall picture of the layout - constitute a complex environment.

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[9] A discussion on routes and maps is given in Chapter 2

[10] The measurement of change would derive from the properties under consideration; for example, if one were planning heating for an environment, air temperature would be a parameter for defining change, and the existing patterns of temperature variation and air currents would contribute to the complexity of the environment.

[11] A convex space is defined as the maximum two-dimensional extension of a space locally, given one dimension [Hillier & Hanson, 1984: 96]; all points within a convex space are visible from all other points assuming 360° vision. This also implies that no information is gained while moving through a convex space, hence making it a *simple* environment (i.e. least complexity).

Hillier and Hanson [1984] formalise spatial complexity in terms of 'symmetrical' and 'asymmetrical' relations between spaces. For example, if A and B are adjacently placed, B is a neighbour of A as A is a neighbour of B, and this constitutes a symmetrical relation. However, this relation becomes asymmetrical if A is placed within B, B cannot be within A, and this relation is asymmetrical with respect to the space that is external to both A and B. Asymmetry is also introduced if a unit C is placed next to B (such that A, B, and C are all on the same plane). In both these cases B obtains a greater value of *neighbourliness* than C and A by being in between. Hillier [1999] suggests that the asymmetry (and hence complexity) of a space is reflected in the number of unique j-graphs that can be formed from the spatial configuration[12].

Considering the numerous spaces and the relations between each of them, it might be suggested that most environments we encounter in our daily lives are reasonably complex in nature[13]. However, for the purposes of this study, complex environments will refer to relatively large buildings as well as urban environments to the extent that they can be navigated without necessarily resorting to survey maps or to other instruments of navigation. That we navigate through such environments with a degree of efficiency has generated interest in the properties of the "mental map"[14] used for this purpose.

Environmental Cognition - Main Strands of Research

> ***"Because we inhabit the environment and need to navigate through it, we need to make sense of it"*** *[Kaplan & Kaplan, 1989]*

A vast number of studies in the fields of neurosciences, geography, robotics, and cognitive psychology have attempted to decipher and/or replicate the human model of spatial representation. Neurologists have attempted to

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[12] It might be suggested that the asymmetrical relation of above/below is similar, if access to 'above' is only through 'below' or vice-versa. For a fuller discussion see Hillier and Hanson 1984; Hillier 1999

[13] It might be suggested that even a convex space becomes complex when the directionality of vision is taken into account, as turning behaviour then has an impact on what is seen and what is not. This suggestion is made with the assumption that this is not an isolated space, so that information about the rest of the environment is gained/lost with movement or turning behaviour in the space.

[14] The idea that people rely on mental models can be traced back to Kenneth Craik's suggestion in 1943 [Craik K. 1943 'The Nature of Explanation' Cambridge University Press] that the mind constructs "small-scale models" of reality that it uses to anticipate events. However, the term 'mental map' was first used by Tolman in a 1948 paper to refer to internally represented spatial models of the environment.

study spatial cognition by observing patterns of human/animal brain activity during spatial activities [O'Keefe & Reece 1993; O'Keefe and Nadel 1978; Burgess et al 1994], while some other studies have sought to derive spatial models from the way space is described in language [O'Keefe & Nadel 1978; Jackendoff 1996; Raubal et al 1997]. Apart from these strands, it might be suggested that there are two major but distinct areas of research into environmental cognition with respect to spatial organisation.

The first might be broadly classified as study into (spatial and non-spatial) factors that affect individual spatial capabilities and spatial reasoning. This research has concentrated on the analysis of individual differences in problem-solving tasks such as mental rotation, pointing, wayfinding, direction giving, or drawing sketch maps [Montello 1991; Golledge 1995; Tversky et al 1999; Conroy-Dalton 2001; Bell & Saucier 2004; Kim & Penn 2004]. However, it might be argued that the ability to form a cognitive representation of space might not necessarily correspond to the ability to externalise that representation, whether verbally, in the form of sketch maps, or otherwise. It is also worth noting that, of the studies looking at the factors affecting spatial capabilities, very few have directly analysed the relation between the spatial layout and the structure of the cognitive map [e.g., Kim & Penn 2004].

The second set of studies investigates the *processes* by which individuals' representations of space might be built. Bordering on Artificial Intelligence and robotics, these studies frequently rely on simulations involving the learning of spatial networks by computational agents or *animats* [Freska 1992; Moose et al 1994; Kuipers 2003]. Though information derived from such computational process models [CPM's] might be used to enrich what is known about the human representation of spatial knowledge, these studies focus mainly upon knowledge representation in order to achieve navigation by *animats*, and more or less neglect the realm of what form the cognitive representation takes, or how far the cognitive mapping of spatial layouts in the generic human brain corresponds to reality.

A somewhat separate set of studies emphasises the human *experience* of the environment [Lynch 1960, Kaplan & Kaplan 1995; Nasar 1998]. While some of these studies have contributed to the development of this field of study in their own right (for example, Lynch's work is seminal to wayfinding research in general), the focus of these studies lies in analysing the relationship of the human *perceiver* to the immediate environment, studying in detail how human preference/taste is affected by phenomena such as sightly/unsightly views, pleasant/unpleasant smells, natural elements such as trees, water, parks, upmarket area/slums, danger, etc[15]. Bordering into the realms of human taste [Bordeau], these studies seem to bypass the issue of how the way in which we make sense of spatial information on a global scale has an effect on the cognitive representation of the surroundings and hence on route-choice.

This study seeks to learn more about the nature of the HCRS and the form in which it is encoded and used. It does so by looking at studies on human movement at the scale of complex environments. The following sections discuss how this generic HCRS might be structured with respect to three attributes: namely - sensory cues/ landmarks; linearity; and the topological, geometrical and metric properties of space. In each the section, the implications of space syntax methodologies will be discussed in further detail, and arguments from cognitive literature put forward to test these. The learning from the various chapters will then be tied together in order to present a model of the HCRS.

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[15] Studies at University College London have shown that these factors are superficial in their impact on movement as compared to configurational properties of space, which can be analysed formally as a system of relations between parts and wholes.

Chapter 2: Informational Layering in the HCRS - Reliance on Sensory Cues & Landmarks

> ***"Wayfinding is surely not a sequence of turning responses conditioned to stimuli. But neither is it the consulting of an internal map of the maze"*** *[Gibson 1979]*
>
> ***"It ... seems unlikely that there is any mystic "instinct" of wayfinding. Rather there is consistent use and organisation of definite sensory cues from the environment."*** *[Lynch 1960]*

That wayfinding and direction-giving are somehow fundamentally dependent upon visual cues or landmarks[16] is often taken for granted both in popular belief and in environmental cognition theory [Lynch 1960; Kaplan, Kaplan 1995; Chown 1999; Lloyd 1999]. However, as outlined above, space syntax methodologies do not take into account the impact of landmarks or other sensory cues upon movement by the generic human being. Contradictory to popular theories and methods adopted in modelling human route-choice and behaviour, this implies that origins and destinations are not fundamental to movement patterns observed on the aggregate level. In addition, if movement patterns are somehow indicative of human cognition of space on an aggregate level, the correlations obtained imply that people do not cognise space in terms of origins, goals, and sub-goals. The other implication is that 'motivation' to take a particular route is not influenced by parks, landmarks, or number of features along the route[17].

This chapter addresses three aspects of the HCRS, first evaluating how far it is based upon procedural route knowledge and the observers' location in the environment. Relevant theories will be introduced to discuss how information acquired discreetly is integrated into a whole, and the way in which informational efficiency can be achieved. Though these ideas will be built upon (more specifically wrt linearity and topology) in the next chapters, this basic structure will provide the basis for assessing the functionality and importance of landmarks within the HCRS. It will be

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[16] It might be noted that the term 'landmark' is defined by the Merriam-Webster online dictionary as "a structure (as a building) of unusual historical and usually aesthetic interest". However, it is used in environmental cognition studies to refer to any form of visual marker that aids decision-making while navigating/ wayfinding. For example, Mataric [1990] defines a landmark as "a feature or location which is robustly and reliably detectable by the sensors". A landmark, in this case, is a visual cue that guides the *animat* with respect to its positioning within the environment.

[17] This is contrary to studies first produced by Lynch [1960] and developed upon by Kaplan and Kaplan [1995], and many others

argued that while landmarks might play a role in executing a sequence of moves along a procedural[18] route, or aid orientation according to a reference frame, they do not form the basis for the formation of an integrated representation of spatial knowledge. Landmark knowledge is hence equated to 'information in space', which forms a subordinate layer in the cognitive representation, its use in verbal descriptions being predominantly due to the non-discursivity of space.

Wayfinding and Navigation - The Human Aspect

> ***"The idea underlying the sense-making method is to look at the wayfinding process itself instead of looking at the final representation."*** *[Raubal et al 1998]* [19]

Siegel and White [1975] suggest that an adult's knowledge of a new environment develops in stages - landmark/place knowledge comes first, followed by route knowledge, and finally, an accurate spatial representation of the area. This is similar to Trullier et al's [1997] suggestion of increasingly complex stages of animat navigation, namely - 'guidance', which is limited to locating oneself with respect to landmarks; 'place recognition triggered response', which is limited to specific responses to stimuli (also known as stimulus-response-stimulus or SRS); 'topological navigation', which is limited to utilisation of segmental route knowledge acquired previously; and 'metric navigation' which is the ability to derive new routes once an accurate 'map' of the area has been formed[20, 21, 22]. Levitt and Lawton [1990] suggest that getting from one place to another involves identifying current location (or an origin), identifying the relative location of other places, and

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[18] Three kinds of geographic knowledge have been suggested: declarative (knowledge of geographic facts), procedural (ability to go from one place to another using a sequence of moves), and configurational (map-like knowledge) [Norman 1988; Mark 1993].

[19] Gluck [1991: 121] states, "Sense-making is a creative human process of understanding the world at a particular point in time and space limited by our physiological capacities, our present, past, and future." Raubal et al use the term 'the final representation' to refer to the cognitive representation.

[20] A 'place' in CPM's might be defined as a set of contiguous locations that are equivalent with regards to the action that is performed by the *animat*. In this sense, it might be equated to the convex space as defined by Hillier and Hanson [1984], each point within which has the same value in a configuration irrespective of size, shape and amount of information available. However, a 'place' in human navigation implies a set of spaces that are grouped as one, for example city centre, work place, neighbourhood; wherever possible, this is referred to as 'area' within this study.

[21] Theoretically, both a computational 'place' and convex space are simple environments, though information perceived from different points within the environment might vary [See Chapter 1].

[22] See: Appendix for a brief overview of animat navigation, Trullier et al [1997] for a comprehensive review of research in the field of CPM's.

deciding upon a route to be taken. However, a few points might be noted. First, it might be suggested that the *animat's* navigational abilities progress in distinct stages, while humans seem to develop spatial knowledge in a more gradual way. Second, unlike *animat* navigation, navigation and wayfinding by humans does not generally require specific positioning in relation to a co-ordinate reference frame in order to identify location. Third, the cases outlined above imply that familiarity with an area would require the use of information other than that gained by direct perception of the environment. However, it is not clear how an understanding of the relative location of other places with respect to an origin is obtained in human navigation.

This is partially clarified by distinguishing between navigation and wayfinding, wherein navigation involves utilising only objects within the range of perception, and therefore does not have any need for the formation of an internal representation of the environment; wayfinding, on the other hand, refers to an environment where there are relevant cues out of the range of perception, and the goal is not within the immediate environment [Prescott 1994][23]. Hence, it might be suggested that procedural memory of routes (or, Stimulus-Response-Stimulus representations such as "go straight for two blocks, turn right at the Hog and Hound") can be useful only while *navigating* between a specific origin and a specific goal, i.e., in environments where the egocentric map can be updated by anticipating the next stimulus. However, it cannot be used for *wayfinding* or planning new routes between locations.

In this respect, O'Keefe and Nadel's [1978] differentiation between routes and maps is especially useful. They suggest that the term route implies specific responses guided by landmarks, which is essentially an egocentric (or, *taxon*) behaviour. On the other hand, maps imply the availability of an aggregate of interrelated information with no necessary specification of guides; maps hence enable the encoding of information independent of the location and orientation from which the environment is perceived (allocentric or *locale* system). However, studies suggest that environmental information is not encoded with sufficient accuracy by humans to allow an accurate representation of space [Golledge 1993; Montello 1997; Tversky

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[23] Prescott [ibid.] suggests that navigation is mostly useful within the immediate or local environment, while wayfinding can be used in moving in a large-scale environment.

2003]. This inability to form an accurate 'map' limits the precision with which new routes can be derived[24]. It might therefore be asked: Do humans rely predominantly upon procedural route-knowledge? Or, is the cognitive representation of space somehow more map-like?

Does a 'cognitive map' exist, or are there just 'cognised routes'?

> ***"Spatial familiarity ... implies an ability not only to recognise and locate phenomena, but an ability to relate phenomena to other places contained in a spatial knowledge structure"*** *[Golledge [1992]*

It might be suggested that visual cues along a route are generally not relevant for navigating the route in the opposite direction, more so if these are distant cues used for orientation[25]. Therefore, a sequence of moves useful for getting from A to B is not necessarily useful for getting from B to A. Further, the usefulness of landmarks varies greatly with direction of movement and approach towards (or away from) the landmark. Since people charting a route in opposite directions will not necessarily see the same objects, it might be argued that procedural route knowledge is not necessarily bi-directional.

This conjecture is confirmed in studies carried out by Golledge et al [1993] wherein participants learnt two routes, both in forward and reverse directions; participants were then asked to differentiate between on and off route landmarks. Errors in inclusions were observed to be greater in the bi-directional case; errors were also found to be greater on one of the two routes. As discussed above, procedural route knowledge and reliance upon landmarks in order to chart a route would require correct sequencing in order to execute the correct response. Since this was not accurately achieved in the bi-directional case, it might be suggested that each route would have to be learnt separately and in both directions for any form of wayfinding ability based upon routes. However, it might be argued that even this degree of procedural route knowledge could not account for human abilities to find a short cut between locations, follow a new route when lost, or explore new territory and return to the point of origin via another route. This seems to

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[24] For a discussion on distance and direction estimates and their use in human environmental cognition: see Chapter 4.

[25] O'Keefe and Nadel [1978: 80-85] utilise an excerpt from a popular book on country walks to demonstrate the non-reversibility of route directions. For example, "walk along the metalled drive" might apply in both directions, but "head away from the church spire" is not as useful as "head towards the church spire".

imply the reliance of cognitive representations on information other than (or in addition to) procedural route knowledge, which is two-dimensional or possibly even multi-dimensional.

In addition, it might be argued that if landmarks do prime response at decision points along a route, they would have to either be encoded separately for every route (in order that they might be easily identified from every major direction of approach towards a decision point), or be unique to the route, or both. It might be asked how this would affect the informational efficiency of the HCRS. The following discussion looks at the informational efficiency of one-dimensional route knowledge, multi-dimensional knowledge, and the feasibility of landmark-based encoding in each of these.

Routes, Maps, Landmarks, & Efficiency

It is widely accepted that humans collate information obtained from discreet sources into an integrated system of information used for wayfinding [Chown 1999; Golledge 1999; Tversky 1999]. It is therefore essential that cognitive processes be structured to minimise information load in order to speed up processing time [Kuipers 1978; Trullier 1997; Chown 1999]. While less information enables decisions to be made more quickly, the lack of precision in making decisions also provides a greater tolerance for error [Chown1999]. However, it might be suggested that some degree of efficiency is also critical.

While routes are the most efficient (least information, most speedily processed) in navigating between a specific origin and destination pair, they are also highly prone to error[26]. In addition, routes are inflexible and are rendered useless if information about any part of a route is lost [O'Keefe and Nadel 1978]. On the other hand, while maps are highly flexible due to their high information content, retrieval of information from a detailed map-like representation of would be slower due to the extra time devoted to processing irrelevant pieces of information. This contrasts highly with the processing of small-scale information relevant to the goal at hand. However, as argued above, only routes learnt separately in both directions could form

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[26] O'Keefe and Nadel [1978] suggest that routes need to be primed with additional information in order to account for lapses of attention and to prevent the eventuality of getting lost. Hence, routes "provide appropriate cautions, 'the old track ... is now elusive', or corrections, 'if you strike the lower road, simply turn right'" [ibid: 84].

a complete set of knowledge of an area. In addition, each route would have to be primed with additional information. On the other hand, information encoded within a configurational representation of space would be flexible for use for more than one purpose.

However, O'Keefe and Nadel [1978] suggest that the *locale* system of the animal (which aids in the formation of an allocentric map) "will act in such a way as to direct the animal's attention away from objects whose presence it can predict towards those whose presence was unexpected". Studies suggest that detail learnt in an environment increases with extended experience in an environment and proximity to the home [lynch 1960; Chown 1999][27]. It has been argued above that the multi-dimensionality of the HCRS provides for a more flexible model than procedural route knowledge, but perhaps not with much advantage in terms of the information-processing requirement. Taking into account the "novelty-seeking"[28] nature of the *locale* system, the reliance of the HCRS upon landmarks would not only result in very low informational efficiency, efficiency would actually decrease as familiarity with the environment increased. Arguably, this is generally not the case with peoples' representations of space.

In addition, it might be suggested that, even when experiencing the same environment, the details learnt and remembered vary amongst people. Studies suggest the existence of a primary (or popular) set of landmarks that are recognised by most people (even those who have never visited the place), and a secondary superset, which are the landmarks recognised by people in the area [Lynch 1960; Golledge 1999]. The latter might be relatively insignificant markers, such as the post-box, or the old elm tree. This implies that the landmarks associated with a place vary greatly from person to person and with experience. It might be argued that the subjectivity of landmarks is an outcome of their non-applicability to the process of navigation by the generic human being. It might therefore be suggested that, while the encoding of detailed information might provide some degree of 'pleasure' or feeling of familiarity, it cannot be considered fundamental to the HCRS.

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[27] In subjects' descriptions of a trip they took from home to their workplace, Lynch [1960] noted a progressive decrease in the *vividness of impressions* as the subjects described locations farther away from home. He therefore states, "Near the home ... there was evidence of daily interest and pleasure in the scene" [ibid: 41].

[28] [O'Keefe and Nadel 1978: 95] refer to the locale system as a "novelty-seeking device".

Therefore, while it can be understood that landmarks (or other cues) prime routes in terms of specific responses in a specific location and direction, they cannot form the *basis* for a generic cognitive representation that can be used for wayfinding in large-scale environments. If this is the case, why are landmarks considered fundamental to the formation of cognitive maps? Or, at what level do landmarks contribute to the HCRS?

The Role of Landmarks in the HCRS

> ***"Knowledge can be distributed, partly in the head, partly in the world, and partly in the constraints of the world."*** *Norman [1988]*

Studies theorise that landmarks act as anchor points for organising other spatial information into a layout, and that large-scale space is represented as a topologically structured collection of landmarks, which in turn aids route planning [Tversky 1993; Chown 1999; Golledge 1999][29]. In suggesting that each place in the cognitive representation is initially identified solely by the presence of a landmark, these studies seem to imply the learning of a *configuration of landmarks,* which in turn aids the estimation of direction and alignment to a reference frame. However, it is arguable whether it is the place that is identified by the landmark, or vice versa. There are two main arguments that might be made against the learning of a configuration of landmarks rather than a configuration of places, and these are presented below.

First, it is common to say that a particular landmark (say, building X) is in a particular place (say, city centre). If one said, "The city centre is around building X", it would sound odd unless the listener recognised only building X. Studies also suggest that directional and distance estimates between specific objects are affected by the relative orientation of the areas that they are located within [Tversky 1992, 1993]. Hence, it seems that the contents of a space are subordinated to the place itself, just as a marble would be to a bag of marbles. It would be quite unusual to state that the bag of marbles is

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[29] Golledge [1999] takes a slightly different standpoint, suggesting that people tend to know routes from their home to workplace, home to the market, and workplace to the market. He implies that while each connection between the 'anchor points' (i.e., work, home, market) might initially be a learnt route, people quickly develop two-dimensional knowledge of the environment in addition to the one-dimensional knowledge of the route itself. He refers to the former as 'learning a route' and to the latter as 'route-based learning of an environment'.

around a specific marble, no matter how large or extraordinary the particular marble was[30].

Second, it might be suggested that people frequently get confused about the exact location of a 'landmark'. For example, one might remember that a particular shop is on a particular street (again, shop is subordinated to street) but not remember which side of the street it is on. Alternatively, one might remember that a particular building is on one of the east-west routes through the city centre, but not remember whether it is the first street on the left, or the second.

Both of the above observations strongly imply that specific locations or landmarks form an upper (subordinate) layer of information embedded in a topological representation of spaces, rather than the other way round. It might be further suggested that landmarks form the "information in space", while a topological representation of the spatial layout is the "information about space"[31] that is essential to wayfinding ability. This also implies that knowledge of the relative location of spaces cannot be equated to knowledge of the relative location of landmarks.

Proposing a Model for the Encoding of Landmarks in the HCRS

Based upon the above arguments, a preliminary model of the HCRS might be proposed (Model 1: below).

Hence, while specific views, signs, sounds, or smells (represented as 'V_A1', 'V_A2'... for the space labelled 'A') might be encoded in memory, they are not essential to the HCRS itself or to wayfinding. This information might be important to *recognising* the final goal (e.g., a specific shop) and navigating towards it but not in comprehension of the spatial layout itself; for example, a specific shop might be searched for on a particular street or in a particular direction. Recognition of specific objects in an area and their location increases with familiarity, while unfamiliar areas will have little or no such

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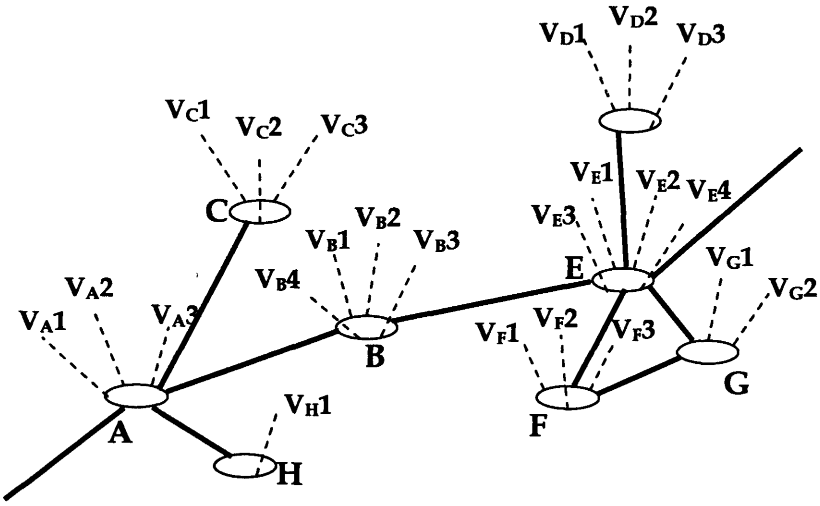
[30] Studies into linguistic patterns seem to suggest that bits of information are chunked into larger groups [Lloyd 1999]. With spatial information, cities are chunked into states, visual markers are chunked together (e.g. a number of shops might be referred to as a market place, or entire areas referred to as city centre, university, etc.).

[31] Norman [1988] differentiates between "knowledge in the head" and "knowledge in the world", suggesting that human beings do not need to have all knowledge in their heads in order to behave precisely. Knowledge in the world acts as its own reminder. It can help us recover structures that we otherwise would forget. He further suggests that knowledge in the head is efficient: no search and interpretation of the environment is required.

information. However, such information is either a way of achieving redundancy at the route-learning stage, or a sign of familiarity; it is unimportant to the overall cognition of place.



Model 1: Configurational knowledge of spatial relations, with visual and sensory cues as additional information encoded with familiarity

However, one obvious question remains with respect to the role of landmarks: if the 'contained' is subordinated to the 'container', why do references to space frequently rely on the objects that are contained in it?

Non-Discursiveness, Direction-Giving, and the Need for Redundancy

It has been suggested that language imposes limitations on the way it is possible to describe and think about space, and to use spatial relationships as a metaphor to express other, non-spatial relationships [O'Keefe and Nadel 1978; Medyckyj-Scott and Blades 1992; Johnson-Laird 1983; Jackendoff 1996][32]. The non-discursiveness of spatial relations provides the basis for speaking about space in terms of objects in space [Hillier 1996; Conroy 2001]. For example, in studies of wayfinding in airports conducted by Raubal et al [1997, 1998], subjects were asked to describe what they saw, their interpretations of the environment, and where they thought they had to go in order to get to a particular gate. The responses were mostly in terms of objects, including signs, colours (e.g., I see the yellow signs), and other objects such as check-in desks, etc[33]. However, very few responses were in terms of spatial qualities, such as "I see a long thin space". It might be

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[32] Jackendoff [1996] claims that it is language that makes thought available to consciousness.

[33] Other responses included: "I see the sign to the B-C gates"; "There are shops"; "I see a way to a sign that says A,C"; "It's an open space"; "The hallway curves around the duty free area"; etc.

suggested that our vocabulary of spatial descriptions is too limited to be able to externalise verbally our internal representation of space. While spatial descriptions are limited to relations like near, far, next to, in between (etc), descriptions of objects within the space can be more elaborate[34]. Hence, it is suggested that the non-discursiveness of space is the reason that people talk about space in terms of objects. It might also be suggested that people mostly talk about wayfinding while giving (or asking for) directions.

Whether given by people familiar with the area, maps or wayfinding services, route directions are meant for people navigating in unfamiliar environments. Therefore, the aim is to recall as much information as possible in order to increase redundancy[35]. Hence, a number of cues (visual and otherwise) might be used in order to aid the otherwise complex task of direction-giving. Statements commonly heard by the author include, 'you will pass a school on the right, it is a red brick building', and, 'take the first left, there is a Starbucks at the corner, the street is called Soho Street'. It might hereby be asked: is the name of the street/area a landmark, or is this just a more discursive way of associating to the place, the purpose perhaps being to be able to ask for further directions in case one got lost?[36]

It might be suggested that once the route has been traversed a few times, the need for redundancy is reduced, making it informationally convenient to think in terms of the spatial layout itself, which is by then encoded as a *non-discursive pattern* and can be recalled as and when required in order to chart the route. While such non-discursiveness is not a hindrance to navigation (as the spatial layout is retrieved and elaborated like a 'map in the head' and does not require the use of language), it only increases the need to rely on landmarks when describing a route to another person. It might be suggested that the reliance on landmarks increases with complexity of configuration. For example, if one comes to a fork in the road, it is easy to describe the

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[34] A detailed discussion of language and spatial discursiveness cannot be encompassed within the scope of this paper.

[35] As suggested above, routes need to be primed with additional information to account for lapses of attention.

[36] It might also be suggested that the need to provide visual marker for a change in direction of movement increases with the number of blocks traversed. Recalling the number of blocks from working memory [Montello 1997] might be influenced by the mode of travel adopted, hence also the need for redundancy. "Follow the road until you come to the school on the left, it is about six or seven blocks, the red-brick building is the school."

choice as, "take the left fork"; however, if one comes to a five street junction, it might be necessary to provide guidance with respect to a landmark.

It is further suggested that even if a route were learnt procedurally, utilising information from prominent landmarks, familiarity with the area would influence route choice differently; these criteria are discussed in the following chapters.

Chapter 3: Towards Linearity in Space

> ***"Directional orientation in 2-dimensional space is a 1-dimensional feature which is determined by an oriented line, an oriented line in turn is specified by an ordered set of two points."*** *[Freska 1992]*
>
> ***"Schematisation entails excluding information irrelevant to the task and simplifying, even distorting, the information important to the task."*** *[Tversky 1999]*

Spatial descriptions often carry implicit information about spatial relationships. Talmy [1983] suggests that the sentence 'she swam across the lake' implies a direct line of travel from one shore of the lake to the opposite shore, so that the line of travel divides the area of the lake into two approximately equal halves. It might be suggested that more often than not, unless detail is explicitly sought after, the representation tends to be both symmetrical and linear.

Various rationales have been provided for the fewest-line axial map and the linear representation of space used by the space syntax theory. Hillier and Hanson [1984] suggest that, in modelling open space as a simplified topological network, the idiosyncrasy of the system is lost; this allows an objective comparison of the inherent structure of the system. While Hillier and Hanson [ibid] are careful not to imply cognition of urban space, it might be argued that some reference to a generic internal representation of space is implicit. Hillier [1999] explains the methodology on purely mathematical grounds, arguing that axial line mapping considers movement from all points to all points in the grid, assuming a 'distance decay'[37] factor in the frequency of trips. Peponis et al [1998] equate axial lines to the availability of information, and use them as a basis for deriving "economic sets of lines"[38]. In contrast to the above studies, Penn [2004] explicitly links the axial line to human cognition of space, equating linear forward motion along a line of

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[37] 'Distance Decay' is a concept frequently used in geography which indicates the tendency for those who live furthest away from the sources of goods and services to consume them less often. This is usually attributed to the increased travel costs or the increased time involved in visiting the source of supply. Also known as tapering, it implies that the longer the distance to be travelled, the lower the frequency of the trip.

[38] Taking the method of axial line mapping one-step further, Peponis et al [1998] propose two other methods of linear mapping: m-lines, which are a least set of lines that can 'see' every surface in the system if a 360° angle vision is considered from every point on each line; and s-lines, which are lines that 'get' everywhere. The latter define the edges or faces of the space where there is a change in the number of surfaces which come into view as the line is crossed, hence, information gained while moving through an environment increases with the number of s-lines crossed.

vision to the least change in 'optic flow'[39], considering 'forward' to be the midpoint within a 170° angle of vision (approximately equal to the visual field of humans). Hence, Penn suggests that information along the axial line is relatively stable, except at intersections where head-turning behaviours are predominant and another line of movement might therefore be adopted.

A number of studies suggest that movement is in some sense linear and two-dimensional [Freska 1992; Frank 1996; Golledge 1992, 1999; Chang 1998; Hillier 1999]. However, directly linking the axial map to human spatial cognition implies that linearity is somehow inherent in the way in which space is encoded by the generic human being. This chapter will test what research into environmental cognition has to say about this. It will be argued that linearity is a tool to counter the complexity of the environment, and that the schematic linearization and chunking together of routes aids efficient retrieval of information.

Orthogonality, Linearity, and Axial Organisation of Space

Cognitive space is popularly conceived of orthogonally along the three major axes of the human body [Sadalla & Montello 1989; Tversky 1999], namely - head/feet, front/back, and left/right. The use of an orthogonal reference frame leads to schematic distortions towards these axes. In addition, spatial relations are relative to a reference frame, which is based upon the viewer in the local environment, and might also be based upon the object or environment in the large-scale environment [Sadalla and Montello 1989; Tversky 2003][40].

According to Tversky [1992, 1999], peoples' tendency to rotate and/or align meaningless blobs like continents towards an orthogonal and upright reference frame is a cause of distortions towards the co-ordinate reference frame[41]. In studies carried out by Lynch [1960], Bostonians misrepresented one major curved avenue as straight, and therefore mistakenly assumed that

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[39] The term 'optic flow' was coined by Gibson in a series of seminal papers on visual perception in the 1960s; Gibson suggests that the reason for our sense of vision is to aid wayfinding.

[40] Tversky et al [1999] differentiate between the space around the body (local environment) and the space of navigation (global environment).

[41] For example, South America is rotated clockwise in people's representations such that a plane dividing it half would be aligned N-S; similarly, a map of the world where Europe has been aligned with North America (instead of being slightly to the North) is chosen as the correct one by most subjects [Tversky 1992, 1999].

all streets intersecting it at right angles were parallel to it. This was not observed in maps of Los Angeles, were the layout was more orthogonal.

Studies suggest that humans comprehend right angle turns more easily than turns that have no obvious reference in relation to their body. For example, Sadalla and Montello [1989] measured error and disorientation associated with increasing angular deviation from either reference axis; the degree of error in judging individual turns increased with degree of deviation from 0°, 90°, or 180° from the direction of motion. However, when judging total angular change along a route, turns between zero° and 90° were all overestimated, while turns between 90° and 180° were all underestimated (zero° equalled straight ahead, while 180° equalled a reverse turn). It might be suggested that both outcomes imply a clear distortion of direction estimations towards the orthogonal axes.

Tversky [2003] suggests that the relative importance of the axes correlates inversely with the time required to recall and respond to queries about objects in imaginary described environments; response times were found to be shortest along the head/feet axis, followed by the front/back axis, while the left/right axis took the longest[42]. Tversky [*ibid*] suggests that axial asymmetries and asymmetries of the world affect response times when organising objects in an egocentric reference frame. However, it might be argued that movement through an environment is strongly biased in the horizontal plane, and is therefore predominantly two-dimensional; if the cognitive representation of space derives from environmental space, the head/feet axis will be the least important in the organisation of environmental spaces as considered in this paper. According to Sadalla and Montello [1978], the equation of vertical with the horizontal yields a "forward up" reference axis that moves through space with the viewer. It might therefore be suggested that, in the organisation of environmental space along the horizontal axes, the front/back distinction is more powerful than the left/right distinction.

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[42] The said environments were described in experiments by Bryant and Tversky [Bryant, Tversky, Franklin 1992; Franklin, Tversky 1990; Franklin, Tversky, Coon 1972; Tversky 1991: as cited in Tversky 2003: 70]. Tversky suggests that response time is faster for the the head/feet axis is an asymmetrical axis and corresponds to the asymmetrical axis of gravity, the front/back axis is asymmetrical with no such correspondence, while the right/left axis is symmetrical with no asymmetrical correspondence.

Such a conjecture is supported in studies of the Hampstead garden suburb [Kim 1999; Kim and Penn 2004], where roads in residents' sketch maps of the area were sometimes curved in the direction opposite to the actual.

In addition, axial analysis was carried out on the residents' sketch maps to analyse their syntactic properties [Kim 1999; Kim and Penn 2004]. It was observed that axial maps derived from the residents' sketch maps frequently had fewer lines; this was either due to depicting roads as wider than they actually were, straightening out curved roads to be less curved, or aligning offset roads to be more in line with each other. However, in all the 73 sketch maps analysed, there was no instance of a street being depicted as a greater number of axial lines than the axial map of the actual layout. It might be worth noting that such linearization of elements was also observed when curves were drawn in the opposite direction to the actual. In similar studies by Milgram [1976], 90% of the participants underestimated the curvature of the Seine River[43]. It can therefore be inferred that cognitive representations of space are schematically (not randomly) distorted towards linearity[44].

Analysing movement patterns in two highly unintelligible areas of London, Chang [1998] observed that people tend to prefer maintaining a straight line of movement over and above minimising the number of intervening junctions passed on a straight line of movement, maintaining a more accurate trajectory, or minimising vertical level changes. This study strongly indicates the need for linearity even though movement in these environments was affected by variables other than axial integration (including step-depth of attractors, the visibility of stairs, etc). Similar results were produced by Conroy-Dalton [2001; 2003] in a wayfinding study in a non-rectilinear virtual environment. The minimum angular route choice available to participants at junctions was 60°, while the maximum was 180°, i.e., straight on. Conroy-Dalton [ibid.] found that the average choice angles at each node tended towards the available maximum rather than towards the mean or minimum. The average angle chosen by participants at each node was also greater than the random choice of angles at each node; the latter tended towards the mean choice angles at the respective nodes. This implies that participants purposefully chose to maintain as straight a line of movement through the environment as they cognitively could. Conroy-Dalton [ibid.] inferred that one reason why people chose to move in as far a

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[43] Milgram [1976] "Psychological maps of Paris" as cited in Sadalla & Montello [1989]

[44] It might be worth noting that the sketch maps are allocentric representations of space.

straight line as they could was to minimise complexity and hence memory load.

First, the above studies suggest that the line is simpler to cognise than other spatial elements; the linearization of routes - and the subsequent simplification of knowledge - therefore serves to meet the needs of informational efficiency in cognitive mapping. . Second, it seems that directional information is chunked together and simplified further. These arguments are further explored below.

Linearity and Information

Studies suggest that cognitive representations of space are qualitative schematisations[45] of reality that entail loss of detail and simplification of information; this in turn allows for efficient memory storage, rapid recall, and retrieval and integration of information from different sources [Chown 1999; Tversky 1999, 2003; Kuipers et al 2003]. The loss of detail is replaced by simplifying distortion, which has a greater degree of tolerance to error [Chown 1999][46]. It might therefore be asked: how does such schematic distortion manifest itself in the selection and mapping of linear routes?

Hillier [1996] presents the paradox of the line, wherein movement along the line seems trade metric integration for visual integration or vice versa; in this sense, it might be suggested that information potential along the line remains constant[47]. In addition, a line achieves co-presence of the greatest number of points in a given space and is therefore the most informationally efficient element that can be defined within the space Hillier [2004]. If the line is one of the simplest spatial elements to cognise and holds the most information along a route, it might be suggested the line (or a network of lines[48]) is probably also the most appropriate for an efficient cognitive representation.

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[45] Freska [1992] explores how qualitative input can provide a quantitative output in a CPM of space.

[46] see ibid: 352 for more detail

[47] The centre point of a line is the most metrically integrated (i.e., closest from all other points on the line), but has the least visual information available considering vision in any one direction; on the other hand, the end points are the most metrically isolated, but with the most visual information available along the line.

[48] The relevance of a topological network of lines to cognition and action is discussed in Chapter 4

At this point, it is worth noting that the presence of "just-about axiality"[49] in cities is a consistent property of the spatial structure, where long lines meet other long lines at obtuse angles. This creates the "slightly sinuous routes" in the spatial structure of the city, which seem to correct themselves to a directed line of movement[50]. It might also be noted that, in experiments conducted in virtual environments by Conroy [2001], maintenance of just about axiality in an environment seemed to be a prerequisite for intelligibility of the environment. Where the just-about lines of vision were interrupted, the environment was highly unintelligible, and participants tended to wander all around the environment while wayfinding. Hence, it might be suggested that axiality seems to be the solution to complexity.

However, the studies discussed above also implied a chunking together of linear information. Hence, it might be asked: does a chunk of linear information function in a way similar to a single line element? Or, how is spatial information that has been schematically distorted into linear elements, chunked together, and then distorted again form a spatial representation that is also efficient?

Linearity, Efficiency, and Angularity

> ***"The paths, the network of habitual or potential lines of movement through the urban network, are the most potent means by which the whole can be ordered ... A straight path has clear direction, of course, but so does one with a few well-defined turns close to 90 degrees, or another of many slight turns which yet never loses its basic direction."*** *[Lynch 1960]*

Studies suggest that humans cognise inter-point distances as crow-fly distances rather than over-the-road distances, and hence derive routes by correcting orientation towards a line connecting their point of origin and destination [Gibson 1979; Golledge 1992, 1995; Sholl et al 2000; Dalton 2001]. While studies involving direction estimation have suggested that humans are able to integrate routes to some degree [Sadalla & Montello 1989; Montello 1991; Bell & Saucier 2004], the errors observed differ greatly with familiarity with the environment as well as experimental setup.

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[49] ,i.e., in self-organised areas of cities, the curvature of streets and the placement of blocks is often such that a line of vision is just about maintained Hillier [1996, 1999].

[50] It might be noted that the major routes connecting the central areas of a city or neighbourhood to the global spatial structure are also the ones that correct themselves more towards a linear direction, or, as argued by the space syntax theory, the routes that are more linear tend to be the major ones because they are more integrated into the entire network and get to more spaces.

Golledge [1992] suggests that the magic number 7±2 is the upper asymptote of route segments that can be learned with relative efficiency and low error. This reinforces the argument that maintaining linear routes minimises informational load and therefore aids more accurate updating of position and direction. However, it might be further argued that the need to restrict the maximum number of segments to be committed to memory provides the rationale behind the chunking of linear information. When charting complex routes, the vectors A→B and B→C might be chunked together as A→C in order to allow more information to be encoded, directional estimates to be made, and a larger cognitive representation to be formed[51].

However, if such linearization in movement is a prerequisite to informational efficiency, the presence of a mechanism to help maintain linearity of route while also minimising directional error seems almost obvious.

As part of a study into the factors that influence route choice (including least distance, fewest turns, longest/shortest leg first, etc.), Golledge [1995] noted whether subjects familiar with an area took the same route as they went from a specified origin to destination and back again. The high degree of asymmetry observed in the choice of routes between one origin-destination pair could not be embraced by either by the desire to minimise metric distance or to minimise turns, as these factors remained constant in both directions; however, the choice of 'longest leg first' was found to account for the asymmetry in the routes taken. Golledge [ibid] therefore inferred that changes in "perception of the configuration of the environment" [ibid: 15] influenced route choice[52]. The 'British Library Theory' [Dalton 2003] accounts for such asymmetric choice of routes by proposing that the choice of 'longest leg first' minimises angular deviation between the goal direction and the initial heading. It further suggests that the inclination to change direction would therefore increase with the angular deviation between the present heading and the cognised direction from the present location to the goal.

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[51] This implies the ability to integrate route knowledge into a seemingly accurate metric representation; it will be argued in Chapter 4 that metric estimates are dependant upon an understanding of the geometry of the system.

[52] This corresponds to Tversky's concept of the 'cognitive collage' [ibid 1992, 1993], which implies the presence of a configurational graph that can be 'justified' according to the observers' location within the environment.

Hochmair [2004] proposes a "least angle heuristic" for computational navigation, concluding that the "'least angle' method leads to the target in most cases and results in the shortest path for most types of street networks". He suggests that, given the choice of two segments with different deviations from the overall trajectory of route, the consequence of taking the segment with the greater deviation would be a metrically longer path to the destination; unless the deviation is quite large[53], this would still enable a comfortable travel distance to be achieved.

It might however be noted that, in unintelligible environments, Chang [1998] found that subjects unfamiliar with the area preferred maintaining a straight line to maintaining a correctly oriented trajectory toward the final destination, with deviations along shorter lines taking place later in the trip to bring one to the destination. It might therefore be suggested that the need for linearity increases with the unintelligibility (or, complexity) of the environment. This strongly implies that even in the absence of appropriate cues (visual or otherwise), linearity serves as a tool to help update observer location and orientation within the HCRS.

Based upon the above, a preliminary model for linearity in the HCRS can be proposed.

Proposing a Model for Linearity in Cognitive Space

Building upon the cognitive dichotomies of left-right (with respect to the line of motion) and front-back, Freska [1992] identifies "eight meaningful disjoint orientation relations" for qualitative spatial reasoning: *straight-front, right-front, right-neutral, right-back, straight-back, left-back, left-neutral, and left-front.* According to Freska, the relations aligned with or orthogonal to the direction of motion (*straight-front, straight-back, right-neutral, and left-neutral*) correspond to a single angle, while the relations *right-front, right-back, left-front and left-back* correspond to an infinitesimal number of angles. However, it has been argued above that most angles cannot be accurately distinguished and distortions towards the orthogonal axes are frequently observed. Evaluating the arguments presented above against Hillier's [1996] observation of just-about axiality in cities, it might be suggested that the set

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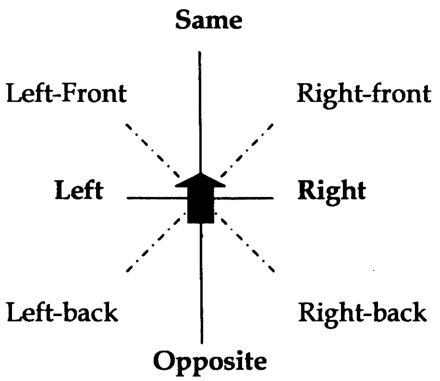
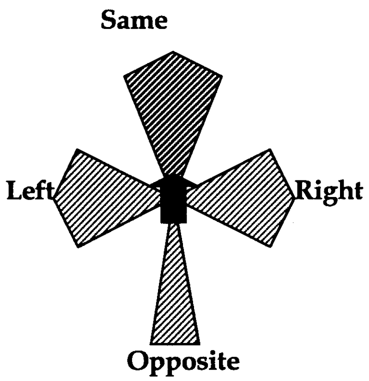
[53] While it is not possible to quantify the term 'quite large' within this study, it might be suggested that angular deviation is accounted for in the model for linearity in the HCRS that will be proposed in this chapter

of angles that actually fall under each category in the generic human cognitive representation would vary with the scale of the urban fabric. Hence, it is proposed that the HCRS relies on easily pliable information similar to model 2 below.



From Freska [1992] – relations in conceptual space for qualitative spatial reasoning



Model 2: This study suggests that a more pliable model is used by the HCRS

Model 2 implies linearity based upon the observer. However, since there is typically no single frame of reference [Kuipers 2003], it might be suggested that such a representation at each point would result in a network of all the longest lines passing through the space[54]. In addition, it might be suggested that each linear representation (right, left, same, opposite) might be a chunking of one or more changes in direction.

It might be noted that this model has yet to be informed by discussions of direction-estimates, metricity, and the integration of spatial knowledge on the cognitive level. However, the discussion above exemplifies that cognitive computation frequently attempts the recreation of human cognitive structures without attempting to first understand the human cognitive process (or, more specifically, the human generic cognitive function)[55].

The derivation of accurate directional estimates from the chunking of linear information seems to imply the encoding of map-like knowledge in the HCRS. Having discussed the unfeasibility of an accurate 'mental map' in Chapter 1, the following chapter will discuss how accuracy can be maintained while allowing flexibility in the cognitive representation.

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[54] It is suggested that this could be similar to the all line axial map [Hillier 1996, 1999]. However, a detailed comparison cannot be carried out as part of this study.

[55] This study uses the term 'Human Generic Cognitive Function' to refer to a specific stage in the human cognitive process, which might be modelled computationally.

Chapter 4: Topological, Geometrical & Metric Information: Levels of Cognition or Cognitive Requirement?

> ***"Any item entering the human memory system gets routed through a series of stores, some organised hierarchically, others in parallel, each analysing and storing it in a particular form."*** *[O'Keefe and Nadel 1978]*
>
> ***"One of the most common assumptions about space, sometimes explicit, more often implicit, is that human spatial organisation is the working out of common behavioural principles through a hierarchy of different levels."*** *[Hillier & Hanson 1984]*

It has been argued in chapter 2 that representations of space are based upon the relative location of places, and are therefore inherently configurational. Chapter 3 suggests that they are also schematically distorted towards linearity. This chapter will look at the topological, geometric, and metric properties of such a representation, and attempt to assess why, as implied by space syntax methodology, the HCRS responds more to the topological and geometric properties of space rather than to its metric properties.

In mapping the entire spatial system as a graph of shapeless and dimensionless nodes, Space Syntax methodology considers *relations of each space taking into account all other relations* [Hillier & Hanson 1984]. However, the adoption of a graph as the representation of space raises two issues.

First, in adopting a graph as a representation of space, the Space Syntax theory assumes that all relations are on the same plane, i.e., the number of levels in a building, the geographical topography of an urban area, and the geometrical layout of a space are seemingly annulled. In addition, the metric properties of spaces are not taken into account, while topological proximities gain importance.

Second, in mapping all relations within a system, a graphical representation considers at the same time the local and the global possibilities for action from a space[56]. For an observer in a complex environment, while the local

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[56] It might be noted here that depth values are based upon the entire configuration of the system, and not upon the connectivity of one line element. The calculation of depth could be up to a particular radius [i.e., number of steps; Radius 3 is usually used to provide a local measure] or up to radius infinity, which takes into account depth of all lines and provides a global picture of the system. Correlations obtained using both radii [Hillier et al 1993; Hillier 2000] hence imply that we are somehow able to grasp both the local and the global structure of space. Since the analyses do not incorporate O-D data, it might be suggested that the structure of the system is somehow grasped in a non-egocentric way [see chapter]

properties of space are perceptually available to the senses, the global properties are not. It might also be noted that, as the global system is grown, properties that are intrinsically local might change drastically. Hence, the potential for action from a space could vary, while the information perceived from a single point might remain more or less the same.

This chapter analyses these issues in the light of the arguments presented above, using literature from Space Syntax and the cognitive sciences to assess how the HCRS responds to these intrinsic properties of space. Arguments for and against the dependency on metric spatial knowledge will first be presented. It will be argued that the HCRS does not rely on exact metric knowledge of areas in order to derive routes. Instead, qualitative information is coupled with heuristics such as 'least angle', 'nearest neighbour', and 'route hierarchy' in order to obtain a metric estimate at various scales. The concept of hierarchical retrieval of information will be introduced as a method of ensuring that only information relevant to the task is processed. It will further be argued that while topologies are essential to the way we navigate space, the chunking of information they entail lead to errors in metric and direction estimates. Geometries, on the other hand, are systemised patterns that are basic to the way we understand navigable space as a whole.

Metricity and Cognitive Space

Euclidean metrics are widely applied to environmental spaces for the purposes of representation (e.g., maps, directions, etc). Studies have therefore argued that cognitive space too must have Euclidean properties [Siegel & White 1975][57]. However, a number of studies suggest that cognitive maps cannot be a one-to-one mapping of physical space on the mental plane [Tversky 1992; Chown 1999; Lloyd 1999], because they contain distortions

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[57] Euclidean space follows four rules:

1. Positivity: Two non-identical points should have a distance greater than zero. i.e., for any two points a and b
   $d(a,a) = 0$ & $d(a,b) > 0$ if $a \neq b$
2. Symmetry: Distance between two points is equal in either direction. i.e.,
   $d(a,b) = d(b,a)$
3. Triangular inequality: That is, for triangularly placed points, the sum of distances between any two pairs of points is always greater than the distance between the third pair. Therefore, for three non-collinear points a, b and c
   $d(a,b) + d(a,c) > d(b,c)$ if $a \neq b \neq c$ & $d(a,b), d(a,c), d(b,c) \neq 0$
4. Segmental additivity: The distance between any two points is the sum of the distance along segments of a path. Therefore, if two points a and c are joined by a segment, then for any point b on the path from a to c
   $d(a,c) = d(a,b) + d(b,c)$

that can only be explained by non-Euclidean metrics [Montello 1995, 1997; Golledge 1999].

Montello [1992] suggests that distance judgements between three triangularly placed points do not conform to a triangular geometry, since the sum of estimated angles between three locations exceeds 180° in several cases; this implies "a spherical geometry of strong curvature" [ibid: 140]. However, other studies argue that violations of triangular inequality in cognitive representations are relatively infrequent [Cadwallader 1979; Golledge 1992; Kim & Penn 2004].

Not much can be said for the consistency of linear distance judgements either. The cognised distance from A→B is not always equal to the cognised distance from B→A [Sadalla & Montello 1989; Golledge 1992]. In addition, the distance from A→C is often estimated to be less than the sum of distances from A→B and B→C (given that B is an intermediate point along the route A→C); Montello [1995] reasons that this is because recall time from Working Memory (WM, required for single distance estimates) is much less than recall time from Long-Term Memory (LTM, required for summing and integration of information from two or more memory sources). Other factors that affect distance judgements along a route include the number of features processed (feature accumulation), the number of turns or junctions encountered (route segmentation), and 'functional effort' required (which might be in terms of time, cost, or physical effort) [Montello 1995; 1997]; each of these contribute to an increase in distance estimates.

The role of 'perspective' in the judgement of distances has also been suggested [Tversky 1992], whereby people tend to expand distance estimates in familiar places, while far-away distances are estimated to be shorter. Golledge [1999] presents three prevalent types of distortions in cognitive representations; he suggests that "fish-eye lens" and "magnetic attractions" type of distortions were commonly observed[58], while a "spaghetti-like" irregular non-Euclidean distortion could be found amongst people who had spent less than six months in the city.

These studies firmly suggest that the HCRS does not rely upon accurate metric knowledge in order to judge shortest route or to aid wayfinding. Contrary to the theories of 'path integration' and 'dead reckoning' as a

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[58] In the 'fisheye lens' type of distortion central distances were overestimated while faraway distances were underestimated; this was reversed for the 'magnetic attractions' type of distortion.

prerequisite to wayfinding[59], the above implies that (unlike a map) spatial knowledge is not an integrated set of information. It is further implied that only information relevant to the task is retrieved; suggesting the presence of some form of hierarchy. In addition, if information is stored and accessed separately, the various types of information might employ different metrics. It might therefore be asked: how is the lack of metric efficiency resolved by the HCRS? Further, how does hierarchy of information play a role?

Resolutions to Metric Inefficiency

> ***"... individuals who learned map information quickly tended to subdivide the map into regions during learning, focus effort on locations yet to be remembered, and use a variety of means to encode spatial information ... "*** *[Allen 1999]*[60]

According to Freska [1992], the goal of a human reasoning process is usually a qualitative result rather than a quantitative one, "qualitative information is obtained by *comparing* features within the object domain rather than by *measuring* them in terms of some artificial external scale" [ibid: 2]. Various studies have proposed heuristics to aid the qualitative minimisation of metric distance. These are evaluated below.

As mentioned earlier, humans find routes by correcting individual lines of movement to approximate a linear direction from the origin to the cognised destination point. However, it might be argued that while minimisation of angular deviation would result in the shortest metric distance in most cases[61], this is highly dependant upon the choices provided by the street network. This implies that apart from configurational knowledge, some degree of accuracy in being able to integrate various types of information acquired along the route is essential; and that this must somehow account for an approximation of the topological, geometric as well as metric properties of space on a sufficiently large scale.

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[59] 'Path integration' and 'dead reckoning' are popular theories in the formation of a cognitive map. Path integration implies an ability to estimate current position relative to a known starting position by computing the displacement through the integration of speed and direction, i.e. through the exclusive use of information gained en route. This process is also referred to as 'dead reckoning', and is used by the animat to keep track of its position relative to the goal or in charting new routes that meet certain criteria such as least distance. For a fuller discussion on the limitations of this model (including the difficulties in integrating place representation with goal location, errors in calculating metric distance, and approximating a continuous point-to-point vector map by an incomplete population of discrete vectors) see Trullier et al [1997]

[60] Allen further states, " good and poor map learners were differentiated by their memory for spatial relations among map features rather than by memory for verbal labels attached to those features." [ibid]

[61] 'Least Angle Heuristic' discussed in chapter 3

The 'Nearest Neighbour Heuristic' (NNH) proposes minimisation of functional distance in the 'travelling salesperson problem'[62] [Hirtle & Garling 1992; Garling 1999]; this is achieved by the 'salesperson' progressively moving from one location to another that is cognitively closest, until all places have been visited or the destination point reached. Garling [1999] suggests that this heuristic leads to adoption of metrically the most efficient route in most (but not all) cases. In addition, it might be argued that by having to process only the locations that are potentially nearest to the present location, informational efficiency is maintained and therefore functional effort is greatly minimised; this is especially important considering that the number of possible connections increases exponentially with increase in the number of places to be visited. It might be suggested that this heuristic represents a topological representation of space with a secondary layer of metric information. In addition, though the representation is seemingly based upon connectivity of all locations to all other locations, consideration is given only to places directly accessible from the current location. This implies the implementation of a hierarchy of choices, where the hierarchy of each node varies with the travellers' position within the network. It is worth noting that this hierarchy functions at the level of information retrieval rather than in the encoding of information.

It has previously been discussed that during exploration representations are based upon the ego or self, consisting only of routes between defined points; however, humans quickly develop two-dimensional knowledge of the surroundings along routes learnt linearly[63]. It might therefore be suggested that the formation of a connectivity matrix of route segments would allow new routes to be derived between O-D pairs that have not been previously navigated. In addition, as physically distant places might be close together in the topological map, topological knowledge of route segments can lead to efficient wayfinding. This forms the basis of the 'Spatial Semantic Hierarchy' (SSH) [Kuipers' 2003]. The following argument assesses the intrinsic properties of the SSH, suggesting that it can form a robust base to learn more about the HCRS.

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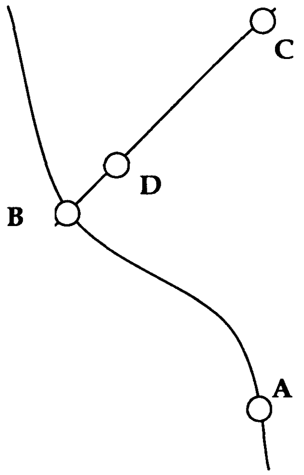
[62] The 'travelling salesperson problem' refers to identifying how people find the shortest distance between a set of locations, each of which has to be visited at least once.

[63] See Chapter 3

Intrinsic Properties of the Spatial Semantic Hierarchy - Application to the HCRS

> ***"Children first develop concepts of proximity, separation, spatial succession, enclosure and contiguity, and these concepts lie within the purview of topology rather than geometry or projective geometry."*** *[Hillier & Hanson 1984: 47]*

Kuipers et al [2003] suggest that expert wayfinders use a 'skeleton' of important paths and places to guide their problem solving; hence, "the expert first finds a route from the initial point to the nearest point on the skeleton, then finds a route within the skeleton to a point near the destination, and finally finds a route from that point to the destination itself" [ibid: 82]. A model of the hierarchy is shown below.



Model 3a: From Kuipers' SSH – geometrical and topological relations in space differ greatly from how they are perceived metrically and egocentrically

A few points from this model might be noted. First, it is apparent that the perception of (and knowledge gained about) the environment from the observers' (egocentric) frame of reference often differs from the object-based[64] or the large-scale environment (allocentric) frames of reference. Hence, depending upon the actual spatial layout, a point that is egocentrically straight ahead of the observer might topologically lie to the right or left of the observer. For example, in the model above, point 'C' lies egocentrically straight-ahead of an observer approaching point 'A' and moving towards 'B'. However, 'C' is topologically to the right of the

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[64] Please note that the object-based frame of reference might be egocentric or allocentric depending upon the actual position of the observer and/or where the observer chooses to mentally place itself in the environment when making a judgement.

observer. Second, the similarity between geometrical and topological relationships is apparent from this model. In the above example, 'D' is metrically and egocentrically closer to point 'B', but it is topologically and geometrically similar to point 'C'. Hence, it might be suggested that the topological and geometric representations exclude information unimportant to the task, simplifying wayfinding. However, it might be argued that the topological nature of the HCRS aggravates errors in direction and metric judgments. This is elaborated below.

The chunking together of linear route knowledge in order to aid the formation of a cognitive representation has been discussed in the previous chapter. It was also suggested that chunking of information can aid in the judgement of direction along a route. It might be suggested that while the accuracy of directional estimates would vary with the number and degree of turns along a route[65], the chunking of information allows for approximations of metric distance to be associated with the topological map[66]. However, studies suggest that the psychological distance between objects is smaller when the objects are in the same subjective region of the space than when they are in different subjective regions of the space, for example, the distance between two cities within a state may be judged as less than the distance between two equally spaced cities that are in different states [Stevens and Coupe 1978[67]; McNamara 1992]. Hence, it might be argued that it is because geometrical and topological representations allow space to be chunked together into parts that are 'similar' to each other that errors in metric judgments are common.

It might therefore be asked: how does the desire to minimize functional distance manifest itself in such a model? Further, how does the introduction of features such as junctions have an impact on the way information is chunked and the consequent estimation of distance?

It might be noted that the efficiency of the route within the SSH is maintained as long as the origin and destination points are on different sides of a path [Kuipers 2003]. However, if both the origin and destination are on the same side of a topological path, the route becomes inefficient. It has been observed that the frequency of appearance of configurational elements

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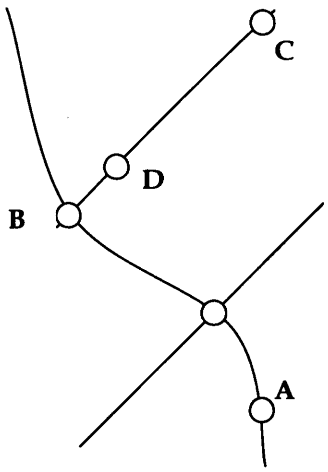
[65] According to the 7±2 principle

[66] While Kuipers' [2003] also suggests that metric distance can be associated with the topological map, he does not elaborate upon a reason for the same.

[67] As cited in Tversky 1993

corresponds to the global syntactic characteristics of spatial configuration [Kim & Penn 2004; Chang & Penn 1998], e.g., the most locally integrated routes also show up on the most number of residents' maps. This implies that wayfinding relies on the judgment and retrieval of the appropriate route hierarchy in order to minimize metric distance. Alternatively, it might be suggested that routes are prioritised according to the hierarchy relevant to the task.



Model 3b: Hierarchical retrieval ensures that only information relevant to the task is processed

It might be suggested that the application of hierarchy in information retrieval also resolves the second question put forward. Hence, the introduction of a feature (e.g., a node) in between 'A' and 'B' would only have an impact upon the topological comprehension of space if the node were relevant to the task. Therefore, if the observer were charting a route from A→B, this additional node would be ignored as irrelevant information. Similarly, nodes C and D would be ignored in task A→B. However, if A→C (or A→D) were being charted, the importance of the additional node would depend upon availability of topological cognized routes towards the destination from this node. It might therefore be suggested that the hierarchy of the layout is structured by the overlaying of segments within our cognitive representations of it. Hence, it might be suggested that the HCRS is a topological map that is also hierarchically structured in terms of what is retrieved and what is not.

This conjecture is supported by findings with regards to route hierarchies for vehicular traffic in London [Penn et al 1998]. In a series of studies of traffic, very little variation between regression equations across a range of study areas in different parts of town was observed. However, Penn et al found that larger radius measures of integration were better related to primary routes (radius 5 to 7), whereas secondary and local streets correlated more highly with a more localized (radius 3) measure. This can be explained by suggesting that the people local to an area (and therefore more familiar) would choose to take the secondary routes, while people unfamiliar with the area would follow the major routes; it is likely that this would also conserve linearity in the routes chosen by the latter[68]. As a result, the global configuration reflects the route hierarchy.

This implies that hierarchical retrieval of information is influenced by relevance as well as by familiarity. It might be further suggested that the information retrieved at any given time influences the cognitive representation of space at that time. While it has been argued above that metrical and directional errors are a result of the HCRS being based upon a topological representation, and that geometrical properties are closely related to topological properties of space, it might be worthwhile to question the role of geometrical information in route-choice and spatial cognition.

Topology, Geometry and Metricity in Direction giving

In order to assess the same, the author's observation of direction-giving in an area is useful. An observation was made of students' responses upon being asked how to get to Gower Street from a mid-point on Gordon Street [see map below]. As per the author's observation, all people mention that Gower Street is parallel to Gordon Street. For pedestrian access, the suggestion is to turn left (into Gower Place) and then left again to get to Gower Street. For vehicular access (for which there is no left turn available in this direction), the predominant suggestion is to loop around the Gordon Square gardens, go down Byng Place, and then turn left down Gower Street, which is a one-way street.

It might be suggested that, in mentioning the apparent parallelism of the two streets, the respondents seem to be clarifying the spatial geometry for the questioner, as an aid to understanding and memorising the given directions. In addition, in giving (the more complicated) directions for the

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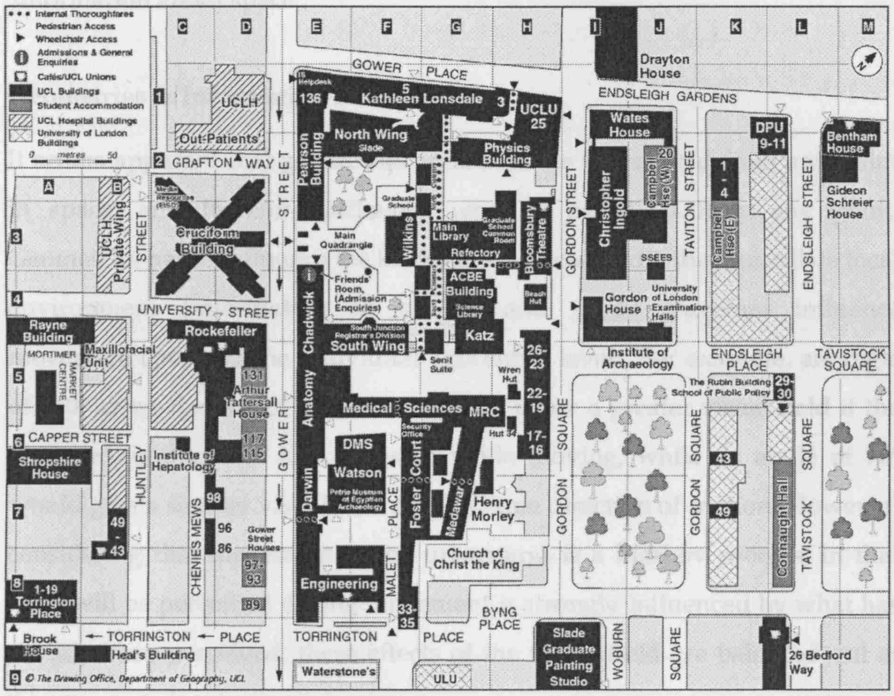
[68] It might be suggested that, as a result, journeys on the primary routes are mainly through movement journeys, while journey on the secondary routes are to- or from- movement journeys.

vehicles, the geometry as well as the general directional orientation seem to play a part in making the structure of the route easier to understand. This seems to imply that while topologies and geometries are closely related, the topological aspects of the space seem to be important to giving directions and to the actual act of navigation, while simplified geometrical information serves as an aid to understanding the spatial layout as a whole and to forming a cognitive representation[69].



Map of Gower Street Area: courtesy ucl.ac.uk

An interesting observation is that very few respondents seem to ask where exactly on Gower Street the questioner intends to go. A direct implication of this is that the suggested routes, while being topologically and geometrically the most efficient, might not be metrically the most efficient. Similarly, the said routes did not mention the distance to be travelled, but the only measures of distance present were in terms of first left/right turn, which implies either equality in perceived block sizes in peoples' cognitive representations, or a disregard for metric distance[70].

In mentioning the parallelism of the streets and the larger spatial structure, the above example also seems to imply that geometries are externalised in

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[69] This is similar to Hanson's [1989] suggestion about order and structure in urban space

[70] The answers were the same regardless of what part of Gordon Street one was on, as long as it was somewhere in the middle. It was observed that people did not mention the routes generally used by students, which cut through the university campus. It might be suggested that these are topologically too complex to be useful in direction giving.

verbal descriptions of the environment; however, they might be simplified and schematically distorted[71]. It is beyond the scope of this study to elaborate upon the argument on space and language. However, it might be suggested that by being semantically encoded into verbal descriptions of schematically distorted space, geometries impart a non-discursive pattern to the spatial layout. The argument below discusses how geometries are related to upper layer 'information in space', and how they supplement topological 'information about space'.

Geometries & Information in Space

It seems apparent that geometries influence the visual field from any point in space, and therefore influence what is perceived from any point. Geometries hence influence the information gained from the immediate local environment (information in space), and might therefore influence movement choice at the individual egocentric level. For example, an angle of 110° along the line of movement would allow a greater visual field if the observer continues to look forward while moving, while an angle of 70° would give a smaller visual field for the same direction of motion. However, considering that movement in the urban grid is a Markov process, in that what will be perceived during movement is strongly influenced by what has already been perceived, these effects of the visual field are balanced out at the aggregate level.

Hence, it might be argued that the topology (information about space) aids in understanding what is perceived from a point in egocentric space, and in relating discreet experiences, while schematic distortions in geometries (verbal or otherwise) enable the pattern to be grasped "all at once" [Hillier 1999]. It might therefore be suggested that geometries are akin to the 'knowledge in the head', 'common sense knowledge', or 'intuitive knowledge of space'[72], that enable one to make sense of topological information. Though the affects of geometry might have an impact on how space is understood by the generic human being, it might be suggested that the effect is only a fine-tuning of the effect of topology on the cognitive representation.

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[71] Ehrlich & Johnson-Laird [1982] suggest that, when presented with a verbal description of a layout of objects, subjects will generate a mental image of the spatial layout, and that their success in forming an accurate mental model depends on the form of the description.

[72] Norman 1988; Kuipers 1978; and Hillier 1999, 2004 (respectively)

Inherent Properties of the HCRS - Thoughts from this chapter

This chapter concludes that geometries are essential to the way we perceive and understand space, while topologies provide possibilities for moving to adjacent places and are therefore essential to the way we navigate in space. Hence, topologies form the 'information about space' that helps make sense of the discreet perceptions involving 'information in space'. Geometries influence the latter by affecting the visual field from any point in space, however, geometries also form schematised non-discursive patterns that aid comprehension of the spatial layout as a whole. However, it has been argued that the judgement of metric factors is highly subjective, and can be influenced by factors other than distance and/or time. It might therefore be suggested that a qualitative approach to wayfinding would therefore incorporate topologies as a distributor of movement, geometry as defining factor for what is perceived and how it is understood, and metricity as a judgement of efficiency not only in terms of metric distance but also time taken to travel, effort, etc.

However, it is suggested that the way in which the space perceived is interpreted is influenced by what has been seen before. This process has been referred to as description retrieval by Hillier [2002, 2003]. The applicability of description retrieval to the human generic cognitive function will be discussed in the following chapter, which gathers the ideas from the rest of this paper, and proposes a model for cognitive space.

Chapter 5: Human Generic Cognitive Function: A discussion

> ***"The structured information on which the system runs is not carried in the description mechanism but in reality itself in the spatio-temporal world... reality is its own programme."*** *[Hillier & Hanson 1984]*

This chapter will gather the ideas presented in this paper, and present a model for cognitive space.

This paper has suggested that the HCRS relies on qualitative rather than quantitative information. The cognitive representation contains both two-dimensional and one-dimensional knowledge that is inherently configurational. This allows topological routes to be derived between O-D pairs that have not previously been navigated, these approximations are also easier to make because they are simplified representations that are informationally efficient. The HCRS is also schematically distorted towards linearity, utilising the least angular change to minimise complexity in its spatial description. Landmarks are used as an aid to navigation in new environments to counter this impreciseness in human judgement of metric distance, increase redundancy in giving directions, and enable discursiveness. It is therefore been argued that the cognitive map is a simplified structure distorted towards linearity, inherently topological, and independent of the specific buildings that stand in the place.

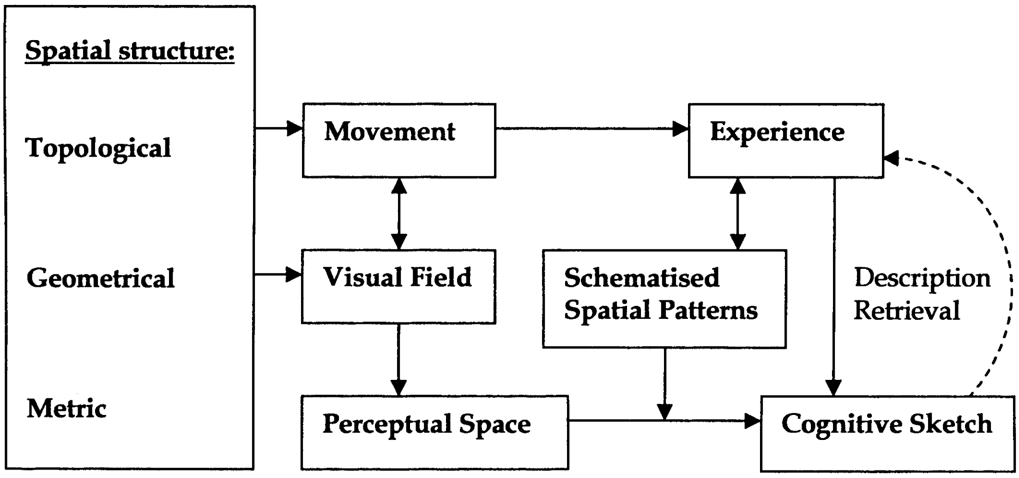
This paper has also indicated that the HCRS can be constructed from incomplete or deliberately randomised environmental information, which is not only hierarchically encoded but also hierarchically retrieved in order to prevent the processing of information irrelevant to the task. This information is influenced by what has been experienced earlier, and the spatial patterns (or, schematised geometries) from previous experiences are superimposed on the information perceived to form a local as well as global representation of space. It is thereby implied that the process of wayfinding differs from the actual cognitive representation, as wayfinding is supplemented by detail present in the world. Based upon the knowledge derived in this paper, a model for the human generic cognitive function is proposed.

Description Retrieval: 'information in space' and 'information about space'

> ***"Ideally a cognitive map should capture some of the flavour of both sets of directions, neither relying completely upon environmental feedback, nor on the precision of what is internally stored."*** *[Chown 1999]*

It has been suggested that geometrical 'knowledge in the head' is generated in the form of *schematised spatial patterns* to enable making sense of 'information about space', which in turn ties together discreet experiences involving 'information in the world'. This common sense knowledge provides an ability to grasp symmetrical and asymmetrical relations in space [Hillier 1996, 1999]. It has been suggested that movement through space is a Markov process, where what comes later is strongly influenced by what has come before. Hence, long lines intersecting at obtuse angles are likely to be followed by more long lines intersecting at obtuse angles, and right angles are likely to follow right-angled turns.

Having argued above that the topological structure contributes to movement, the geometrical structure to the visual field, and the cognitive judgement of metricity to route-choice within urban space, a cognitive process like the one below might therefore be proposed.



Model 4: The functioning and development of the human cognitive representation of space

According to this model, movement provides experience of places, which can be stored in the form of patterns to prime future experiences[73]. The visual field in turn provides a perceptual space, which is informed by

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[73] Though it is suggested that movement and the visual field influence each other to some extent [Turner et al 1999, 2001] this paper leaves this open to further research.

existing spatial patterns or schematised geometries and provides a cognitive sketch of the space. The cognitive sketch is constantly modified by experience, which also aids the formation of schematised spatial patterns. These patterns form the common sense knowledge in the head. This two-way process of using prior experience to make sense of the present, and using the present to build upon previously experienced patterns might be referred to as description retrieval in the human generic cognitive function.

Reflections & Further research

This study has proposed a model for the human generic cognitive function based upon the three specific research questions stemming from current research in Space Syntax. These questions have helped clarify and distinguish the role of spatial and spatially-organised elements in human cognition.

However, it was noted in Chapter 3 that CPM's often attempt to emulate the human generic cognitive function without trying to understand the process itself. It is therefore suggested that using the model(s) proposed as part of this study might not only aid computational process modelling, but would also put the models proposed to the test. The outputs could then be used in gaining a better understanding of human cognition at the generic level and the HCRS.

In addition, it might be useful to re-assess the proposed model in the light of the few relevant questions that could not be researched within the scope of this study.

The first deliberation is from chapter 4, where it was suggested that while metricity might not always form part of the cognitive representation, it might influence the cognitive representation as far as scaling in navigable environments is concerned. Contrarily, this also suggests that cognitive representations on a larger scale would tend to be more distorted or linearised.

It might also be suggested that description retrieval and the reliance of the human generic cognitive function on previous experience seem to imply that the HCRS would differ with the spatial layout experienced. Hence, the cognitive representation of a person from a predominantly orthogonal-grid city like Manhattan might be different from that of a person from a deformed-grid city like London. This conjecture seems to link research into spatial cognition with research into urban form.

Lastly, as suggested earlier, the intention of this paper has been to consider the HCRS solely at the level of the generic human being. However, it might be asked: Can Space Syntax also tell us something about the individual cognitive representation of space? Or, to what degree are individual intents implicitly or explicitly present within Space Syntax methodologies? These questions are left open for further research.

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Appendix 1: Space Syntax Representations: A Review

Space syntax representations model open space as a set of discrete elements. While the exact method chosen depends upon the requirement of the study, three common representations are:

> (1) Convex space analysis [Hillier & Hanson 1984] chunks space into the fewest and fattest *convex* spaces, each of which is represented as a node, and adjacent spaces are connected by a link;
>
> (2) The fewest line axial map [Hillier and Hanson 1984; Hillier et al 1993; Hillier 1996] represents space linearly as the fewest and longest lines that are required to traverse all convex spaces in the system, minimising depth where possible; each of these lines is a node while the intersections are the links; and
>
> (3) The Visibility Graph Analysis (VGA) [Turner, Penn 1999; Turner et al 2001] divides space into a fine tessellation of points, each of which is a node; the nodes *visible* to each other (i.e., accessible in a direct unobstructed line) are connected by a link.

In the representations mentioned above, each unit of space is considered a node, and has no dimension. Depth from all nodes to all nodes is calculated and summed to give a total depth value for each node. The space with the least depth from all others has the highest *integration* value (also known as measure of *accessibility*). Theoretically, this space is easy to get to from all spaces, and experiences the most to-movement[74].

In an additional measure used in axial mapping, the shortest topological path between each pair of nodes is calculated (i.e., each node is an origin and a destination from each of the other nodes in turn). The space lying on the simplest topological path between largest number of origin-destination pairs is said to have a high *choice* value (also known as measure of *betweenness*).

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[74] It is worth noting that in the mapping process described above, the convex space is a local element, while the axial line is the most global and can be considered to pass through many convex spaces. Also, while the VGA analysis breaks space into local elements, distant nodes which are visible from each other are effectively considered next to each other, making this a somewhat global measure. However, the axial map is the 'urban workhorse' of space syntax methodology, having produced robust correlations with aggregate movement at the scale of complex buildings and urban layouts [Hillier et al 1993, Penn et al 1998].

Theoretically, this has the most number of routes[75] passing through it, and therefore would experience the most through-movement.

It might be noted here that the space syntax methodology is based upon random movement from every point in the grid all others, assuming a '*distance decay*' factor in movement [Hillier 1996, 1999, 2004]. Though the methodology does not make any assumptions about the human and/or cognitive factor in movement, there has been debate whether the correlations obtained are solely *network effects* (i.e., that lines which are better integrated into the entire network experience more movement simply due to a greater number of routes passing through them as per mathematical probability) or whether the human comprehension of space is somehow implicit in the methodology.

It is with the fewest-line axial map that the disregard for metric distance is the most apparent, since lines are reduced to dimensionless nodes regardless of whether they are the long lines that intersect many other lines or the very short lines that form the dead-end spaces. Studies argue that the longer lines also tend to intersect with a greater number of lines along their entire length, and would therefore have a high connectivity and a higher integration value [Hillier 1999; Penn 2001]. In addition, since the measures take into account relations between all elements, the immediate connectivity of the line is not the only justifying factor in the value of integration obtained [ibid.]. However, the latest research uses the *Segmen* model [Hillier & Iida 2005], which converts each individual line element into discrete segments, the ends of which are defined by the intersections between the lines. The same model can be analysed for its topological (fewest turns), angular (least angle change) and metric (least distance) properties from all spaces to all other spaces in the system. The fact that movement correlates with the three properties consistently and to varying degrees strongly implies the presence of more than one operational factor guiding movement through the urban space. Hillier and Iida [ibid.] suggest that the methodology takes into account both a mathematical distribution of movement, as well as the human cognitive factor.

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[75] The term 'route' is extensively used in cognitive literature to imply stimulus-response based learning and navigation [O'Keefe and Nadel 1978; discussed in section X]. However, here the term implies one of many potential paths from an origin to a destination.

Appendix 2: The Development of Environmental Knowledge in Animats: An Overview

Trullier et al [1997] suggest four increasingly complex navigation behaviours for *animats*: 'Guidance' (limited to following cues within the local environment); 'place-recognition-triggered response' (limited to wayfinding without planning); 'topological navigation' (limited to using known paths); and 'metric navigation' (ability to plan and chart a route once a detailed spatial map has been acquired).

'Guidance' behaviour by an *animat* relies upon memorising the relationship between itself and certain environmental cues at a specific location. Hence, the *animat* moves to the position where the relationship was memorised, maintaining a particular distance from one or more identified locations; this leads to behaviours like wall-following, etc[76]. This process has also been referred to as *landmark guidance* [Collet 1992].

Following a route involves learning specific responses to stimuli, which might be visual or otherwise (sound, smell, slope, etc) [O'Keefe and Nadel 1978; Mataric 1990; Kuipers & Byun 1991]. Trullier et al [1997] suggest that a place only needs to be recognised as a *situation* experienced previously in order for a movement selection procedure to be applied; this is known as 'place-recognition-triggered-response'.

Kuipers et al [1978] model such procedural knowledge of space as a collection of 'view-action pairs'. Hence, the animat 'expects' each progressive stimulus and executes the required response to reach a particular goal. This is similar to the Stimulus-Response-Stimulus (or, SRS) theory put forward by O'Keefe and Nadel [1978], which forms the basis of 'topological navigation' in *animats*. This allows new routes to be derived from partially overlapping routes that have been charted previously.

The final and most complex stage in *animat* navigation involves the formation of a complete map that allows the animat to plot new routes based on certain criteria (shortest distance, fewest turns) from the information acquired previously. However, the generation of such maps from knowledge of routes requires precise identification of location,

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[76] Cartwright and Collet [1983]; Collet [1992] as cited in Trullier et al [1997]

orientation, distance and movement, in order that the information from various sequential routes can be effectively integrated and utilised[77].

While most CPMs simulate the learning process at different levels of their spatial representation, it might be suggested that animat navigation relies heavily upon recognition of 'places', which is achieved by using visual cues such as landmarks/landmark configurations[78] and the corresponding place fields. It might also be noted that guidance, place-recognition, route following and layout learning are distinct stages in animat navigation.

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[77] For a more detailed discussion on animat navigation, see Trullier et al [1997]

[78] 'Landmark configuration' in animat navigation refers to the image(s) projected on the visual plane by a group of landmarks, and is a key method of initiating place-recognition.