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Research Article

Cognitive models of geographical space

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Abstract. This paper reviews research in geographical cognition that provides part of the theoretical foundation of geographical information science. Free-standing research streams in cognitive science, behavioural geography, and cartography converged in the last decade or so with work on theoretical foundations for geographical information systems to produce a coherent research community that advances geographical information science, geographical information systems, and the contributing fields and disciplines. Then, we review three high-priority research areas that are the topics for research initiatives within the NCGIA's Project Varenius. Other topics consider but ranked less important at this time are also reviewed.

1. Introduction

As geographical information becomes ubiquitous in a variety of domains and field applications, computational models of geographical cognition become increasingly important to the growth of a science of geographical information. This paper reviews the history of research in cognition of geographical space, summarizes the current state of the field, and suggests several important open issues regarding the cognitive component of geographical information science.

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It is important to recognize the distinction between geographical space and space at other scales or sizes. Palm-top and table-top spaces are small enough to be seen from a single point, and typically are populated with manipulative objects, many of which are made by humans. In contrast, geographical or large-scale spaces are generally too large to be perceived all at once, but can best be thought of as being transperceptual (Downs and Stea 1977, p.197), experienced only by integration of perceptual experiences over space and time through memory and reasoning, or through the use of small-scale models such as maps. Some of our discussions of geographical cognition might not apply to spatial cognition at other scales.

Our review of cognitive models of geographical space is made in the context of providing a sound theoretical foundation for geographical information systems (GIS). The First International Advanced Study Symposium on Topological Data Structures for Geographic Information Systems, organized and hosted by Harvard University in October 1977, included many papers that raised theoretical issues about the nature of geographical information and of computational systems to deal with it. Among the more important papers in this vein are those by Chrisman (1979), Kuipers (1979), and Sinton (1979). Kuipers' paper in particular established a cognitive component to these theoretical foundations. Also in 1979, formal topological foundations for GIS were published Corbett (1979). Boyle *et al.* (1983) stated that progress in GIS was impeded by a lack of theory. In that same year, Jerome E. Dobson published his now famous 'Automated Geography' paper in *The Professional Geographer*, raising the idea that widespread adoption of computational models was changing the discipline (Dobson 1983). Around 1987 there was a flurry of publication activity (Abler 1987, Frank 1987, Peuquet 1988, NCGIA 1989).

The idea of a science of geographical information, a scientific or intellectual field behind and around geographical information systems, emerged rather suddenly in the late 1980s, perhaps as part of the maturation of theory and intellectual content in GIS. Michael Goodchild's July 1990 keynote address at the Spatial Data Handling international symposium in Zurich was entitled 'Spatial Information Science'. The word spatial was changed to geographical as Goodchild's keynote became an article (Goodchild 1992), and in a few short years, a new field of study, a new science, had emerged. For a further review of geographical information science (GIScience), see the introduction by Goodchild *et al.* in this issue.

The idea that a science of geographical information should have a cognitive foundation emerged with the development of GIScience itself in the late 1980s, when it was included in the successful proposal for the National Center for Geographical Information and Analysis (NCGIA 1989). The National Science Foundation's solicitation for proposals for an NCGIA included five main topics (bullets) characterizing key areas for research by the Center. One of these topics was to research and develop a 'general theory of spatial relations and database structures'. The successful bidders for the NCGIA argued that such a theory must necessarily include a component that linked cognition and computation, and outlined a research initiative called 'Languages of Spatial Relations' (Mark 1988, 1989, Mark *et al.* 1989, Mark and Frank 1990, 1991), the second research initiative undertaken by the NCGIA.

A direct attention to cognitive issues in the GIS discourse appears to have originated in the mid-1980s, when GIS researchers saw the potential of cognitive science to provide insights on how to develop a richer theoretical basis than could be provided by Euclidean geometry and graph theory. The first papers clearly identifiable with this theme were V. B. Robinson's work on fuzzy logic models of the meanings of spatial relations (Robinson *et al.* 1985, 1986a, b). Smith *et al.* (1987) described a knowledge-based GIS that included many cognitive concepts. Shortly thereafter, papers on cognitive aspects of geographical information science were presented at an international meeting in Crystal City, Virginia (Frank 1987, Mark *et al.* 1987).

Cognitive geography and geographical cognition is a very broad topic, and some aspects of geographical cognition are of only marginal relevance to geographical information science. Some of those more peripheral topics are excluded from this review, although they are important topics in their own right, and may eventually prove critical to a complete cognitive foundation for geographical information science. One set of such topics are those that deal with neurophysiology and neuropsychology. Although the physiological architectures of human cognitive systems may eventually provide explanations for observable aspects of human spatial cognition and behaviour, we have decided to exclude them from the study domain because at present their relevance is peripheral. Furthermore, current methods of instrumentation for brain observation do not generally provide sufficiently detailed measures of localized activity in the brain to provide insights at the level of current questions in geographical information science. Secondly, we exclude cognition of spatial relations and positions at astronomical scales—whereas they are also of potential interest, such spaces are so unlike terrestrial spaces that their inclusion here would be unlikely to provide insights for geographical cognition. And third, we exclude reasoning about purely geometric figures and patterns, again because of marginal relevance and space limitations, although, given the close ties between geographical reasoning and geometric reasoning, including the newer field of diagrammatic reasoning, we have included selected papers in cases where such papers provide useful insights into map cognition or geographical cognition.

In the remainder of this paper, we first provide a history of the field, including the several independent research threads that converged in the 1980s to produce a cognitive research theme in geographical information science. Next, we discuss the major research themes in cognitive geography and geographical cognition today, under the headings of acquisition of geographical knowledge, mental representations of geographical knowledge, geographical knowledge use, and communication of geographical information. Then, in the last main section of this paper, we review the major topics considered for investigation under the Varenius project (Kemp *et al.* 1997), emphasizing the three researchable topics identified under the project, and mentioning other topics considered.

2. History of the field of geographical cognition

Maps have been used to provide external representations of geographical information for thousands of years, and Thrower (1972) provides an excellent review of the history of maps. Also, as revealed by its etymology, geometry itself is said to have had its origins in land surveying after annual floods of the Nile river. Connections between geospatial cognition and human activity and survival are even more ancient. Although many aspects of this may be universal, researchers have found wide cross-cultural variation in how geographical space is conceptualized for tasks such as navigation (Gladwin 1970, Lewis 1972), and research on cognition and behaviour at geographical scales developed in several fields and disciplines. In the remainder of this section, we review some of the research streams that came together in the 1980s to form a cognitive foundation for geographical information science.

2.1. *Spatial cognition research in psychology*

The origins of psychology as a scientific discipline are variously dated to the founding of Wundt's laboratory in Leipzig in 1879 or to the publication of James' Principles of Psychology in 1890 or to the founding of the American Psychological Association in 1892 (Hilgard 1987). Although cognitive psychology can be traced back as far as nineteenth century Germany, to the psychophysics studies of Weber, Fechner, and Wundt, to the mental operations studies of Donders, and to the experiments on memory of Ebbinghaus, its continuity was interrupted by the hegemony of behaviourism. The modern origins of cognitive psychology date from the 1940s and 1950s. Two parallel but unrelated strands united in the development of theories of information processing. One strand was practical, growing out of the human factors work that was part of the war effort. The other strand was theoretical, primarily borrowed from information theory and formal linguistics. These strands were woven together by George Miller (e.g. Miller 1956) and his colleagues and students in the United States, and Donald Broadbent (e.g. Broadbent 1958) and his colleagues and students in England, among many others. If an official date is needed, the publication of Neisser's book *Cognitive Psychology* (1967) serves as well as any for the beginning of cognitive psychology as a separate field.

The pursuit of spatial cognition was delayed even after the restrictions of behaviourism were overcome, due to a bias among many leading researchers based on the idea that the underlying language of thought was like language, and that the visual and spatial world could be reduced to language processing. Research on imagery provided a persuasive case that, at best, such reductionism ignored the truly fascinating issues (Kosslyn 1980, Shepard and Podgorny 1978). In the background, developmental psychologists were rediscovering Piaget, including his work on children's concepts of space. At the same time, geographers were investigating how people perceived and remembered the geographical world, and neuropsychologists were recording activation in rats' brains as they learned mazes (O'Keefe and Nadel 1978).

2.2. *Cognition of geographical space*

Trowbridge's (1913) early paper aside, many people would date the modern period of cognitive studies of geographical environments to the work of E. C. Tolman. His classic 1948 paper 'Cognitive maps in rats and men' introduced the term 'cognitive map', and made an explicit link between experimental behaviour of laboratory animals on the one hand, and wayfinding and navigation abilities of people on the other (Tolman 1948). Two other early benchmark works of great influence were Piaget and Inhelder's 1956 book *L'Espace Chez L'Enfant* (translated as *The Child's Conception of Space*; Piaget and Inhelder 1956), and Kevin Lynch's 1960 book *The Image of the City* (Lynch 1960). Piaget and Inhelder were psychologists, but Lynch was an urban planner and landscape architect.

The period 1978–1985 saw serious empirical work on geographical cognition being conducted and published by psychologists. Most of these efforts were aimed at revealing how environments are mentally represented, by focusing on distortions in judgements about the environment. Stevens and Coupe (1978) were among the first to provide empirical evidence of hierarchical spatial reasoning, and showed how this powerful heuristic can distort judgements and memory of spatial relations. Hirtle and Jonides (1985) showed that hierarchical organisation can be based on function as well as boundaries, and that it affects distance as well as direction judgements. Evans and Pezdek (1980) used reaction times to study distance judgements, finding evidence for mental rotation effects for environments learned from maps but not for environments learned from experience. Tversky (1981) presented evidence that perceptual organizing principles can distort judgements of spatial relations. For example, Americans typically think that South America is aligned directly south of North America, when in fact most of South America is much further east. Holyoak and Mah (1982) showed that the perspective taken on an environment distorts distance judgements, so that near distances are judged to be relatively larger than far ones. Thorndyke and Hayes-Roth (1982) studied acquisition of environments from maps or exploration. They found superior direction judgements in the group that learned from exploration, and superior straight-line distance estimates from those who learned from maps. Kozlowski and Bryant (1977) found that people's estimates of their senses of direction predicted acquisition of a computer maze. There are several reviews of this foundational literature, including those by Evans (1980), Golledge and Stimson (1997), Downs and Stea (1977), and Tversky (in press, (*a*) and (*b*)).

2.3. *Behavioural geography*

One can find some evidence that individual geographers were interested in behavioural research before 1960, with work on imaginary worlds (Wright 1947, Kirk 1951) and the perception of hazardous environments (White 1945). However, behavioral research became an important part of the discipline of geography during the 1960s and 1970s. Research in the 1960s related to images of the city (Lynch 1960), environmental images (Lowenthal 1961), decision-making processes (Wolpert 1964), and mental maps (Gould 1966) inspired a generation of geographers to consider behavioural issues. They were soon applying new methods to old ideas (Rushton 1969) and relating concepts developed in behavioural geography to more-mainstream geographical problems (Horton and Reynolds 1971). Blaut and Stea (1971) published an important article that was an early presentation of cognitive foundations for geographical learning. A number of books appeared that formed the foundation of this new behavioural interest. Cox and Golledge (1969) considered the behavioural problems in geography. Geographers and psychologists began to collaborate in the 1970s, and some of these collaborations gave rise to books that considered their common interests in learning about the geographical environment, cognitive maps, and spatial behaviour (Downs and Stea 1973, 1977, Moore and Golledge 1976).

Although early behavioural geography has had both its critics (Bunting and Guelke 1979) and defenders (Downs 1979, Rushton 1979, Saarinen 1979), behavioural geography has continued to grow and make progress (Aitken 1991, 1992, Kitchin 1996). Behavioural topics considered by geographers expanded into a variety of interests in the 1980s, including earthquake hazard information (Palm 1981), the use of imagery to store geographical information (Lloyd 1982), the spatial abilities of the sexes (Gilmartin and Patton 1984), consumers' cognition of distance (Coshall 1985), and the influence of anchor points in the environment (Couclelis *et al.* 1987).

The current decade has seen more collaboration between geographers, psychologists, computer scientists, linguists, and others with a focus on spatial cognition. A special issue of *GeoForum* in 1992 presented a collection of papers related to cognitive issues. A book edited by Gärling and Golledge (1993) presented both geographical and psychological approaches to studying behaviour and environment. Portugali (1996) edited a book on the construction of cognitive maps, with chapters by both geographers and psychologists. Other recent books providing a geographical perspective to cognitive issues are by Golledge and Stimson (1997), Lloyd (1997), Golledge (1998), and Kitchin and Freundschuh (in press). For a review of behavioural geography within American academic geography, see Golledge and Aitken (1991).

2.4. *Cognitive research in cartography*

Although studies on the perception of orientation (Gulliver 1908) and imaginary maps (Trowbridge 1913) showed an early interest in the cognitive processes used in map reading, cartographers did not demonstrate much additional interest in cognition until the 1970s. An important exception from the 1950s was a landmark study of distortions in perceived sizes of cartographic symbols. Flannery (1956, 1971) examined graduated circles, a cartographic symbol technique which originally scaled circles so that their total areas were in linear relation to some quantity being symbolized, such as city population. Flannery noted a tendency to underestimate the relative sizes of larger circles, and he calibrated this perceptual bias using psychophysical laboratory methods. The result of his work was to add to conventional cartographic practice a rule whereby radii of graduated circles were scaled in proportion to 0.57 times the logarithm of the quantities they were to represent (Robinson 1960). This correction introduces a systematic geometric exaggeration of larger circles, in principle to compensate in advance for the underestimation evidently found in normal perception. In a communication model of cartography, if the decoder (human perception during map reading) is known to introduce systematic distortions, then the inverse of the distortion should be used when constructing the map, so that the perceived map is unbiased.

Maps must provide accurate information to be useful, but they also must have an understandable message and be aesthetically pleasing. When cartographers began to study the nature of maps to understand symbolization and design principles (Robinson 1952, Robinson and Petchenik 1976), this resulted in an appreciation of maps as communication tools (Board 1967, Kolány 1969) and the discovery of a need to understand the cognitive processes used by map readers. To fulfill this need, some cartographers embraced an experimental paradigm and studied the interaction between the map and map reader. Sheppard and Adams (1971) studied drivers' use of road maps for route finding. Other important early issues were the organization of information (Dent 1972, Lloyd and Yehl 1979), the perceptual response to cartographic symbols (Cox 1976, Gilmartin 1981, Kimerling 1985), and the visual comparison of maps (Lloyd and Steinke 1977, Muehrcke 1973).

In additional to being familiar with computer graphics technology, the current generation of cartographers must be part artist and part cognitive scientist as they try to construct better maps (MacEachren 1995). Some of the cognitive topics recently considered by cartographers include use of colour on maps (Brewer *et al.* 1997, Brewer and Olson 1997, Mersey 1990), visual search processes used in map reading (Nelson 1995, Lloyd 1997), and learning processes used with maps and graphics (Lloyd 1994, Lloyd and Carbone 1995). The idea of using visualization to discover patterns has only recently been discovered by a number of disciplines, but is an old and familiar concept for cartographers (Monmonier 1990, MacEachren and Taylor 1994). The design and use of interactive maps (Slocum and Egbert 1993, Patton and Cammack 1996) and map animations (DiBiase *et al.* 1992, Peterson 1995) have been of particular interest to cartographers.

2.5. *Artificial intelligence in geographical contexts*

As the field of artificial intelligence matured, the knowledge representation and processing methods developed in the laboratory were applied to real world problems in the 1970s. Several applications to geographical information became visible. In 1978, Benjamin Kuipers published an elaborate model for representing human knowledge of large-scale space in an artificial intelligence framework (Kuipers 1978). Kuipers' model built largely on the intuitive and descriptive work of Kevin Lynch (1960). In a follow-up paper, Kuipers discusses the 'map in the head' metaphor frequently employed to account for people's ability to find their way in space (Kuipers 1982). The author uses computational models to refine the too simplistic metaphor and to discuss its implications in detail. In a subsequent paper, Kuipers discusses cognitive maps, their structure, and potential alternatives by employing a thought experiment in robotics (Kuipers 1983).

Davis (1983, 1986) looked at a cognitive map as a knowledge base; he developed a theory of representation, retrieval, and assimilation of geographical knowledge and implemented his theory in the MERCATOR system. MERCATOR is conceived for the use by a robot whose task is to build up a coherent representation of his visually perceived environment. Yeap (1988) also developed a computational theory of cognitive maps. Yeap's work emphasizes the cooperation of different loosely coupled modules representing different levels of information. The approach is motivated by Marr's (1982) investigations into the human representation and processing of visual information. Finally, Munro and Hirtle (1989) and Wender (1989) have developed connectionist models of cognitive maps, in contrast to the symbolic approaches listed above.

Critical evidence from linguistics entered the picture in 1983 with Leonard Talmy's seminal work on how space is structured in language (Talmy 1983). This paper started the important cognitive–linguistic research thread in cognitive geographical research. The artificial intelligence system CITYTOUR (André *et al.* 1987) was designed to answer natural language questions about the spatial relationships between objects in a city. Approaches from artificial intelligence were also applied to classic problems in cartography, especially automated name placement and other aspects of map design (Freeman and Ahn 1984, Buttenfield and Mark 1990). Couclelis (1986) reviewed artificial intelligence in geography during its early stage of widespread impact in the discipline.

2.6. *Wayfinding and navigation*

Wayfinding, defined as the mental processes involved in determining a route between two points and then following that route, has long been an important site for studying spatial cognition. Kevin Lynch's 1960 book *Image of the City* paid particular attention to making cities more navigable. In a dissertation aimed at modelling common-sense reasoning in general, Benjamin Kuipers chose learning the geography of a place as a case study. The main results were published in a journal article already mentioned, that was to have considerable influence on the field (Kuipers 1978). Shortly after the publication of that work, Riesbeck (1980) described a related problem and implemented a system to judge the clarity of driving directions, given no knowledge of the actual geographical layout.

In the 1980s, the development of microcomputers made it possible to consider designing navigation aid systems for private automobiles, that would keep track of the location of the vehicle, relate that position to an on-board digital street map, and provide navigation assistance to the driver. An obvious way to communicate with the driver would be to display maps, and this was the design of early implemented systems such as Etak's Navigator (Zavoli *et al.* 1985). A parallel line of work developed systems to provide verbal descriptions of routes, mainly to give to someone renting an automobile and requiring directions to some attraction. Elliott and Lesk (1982), Streeter *et al.* (1985), and Streeter and Vitello (1986) all studied the nature and content of driving directions, and related these characteristics to principles of knowledge representation in artificial intelligence. This line of work was picked up by people in the GIS community (Mark 1985, Mark and McGranaghan 1986, Mark *et al.* 1987, McGranaghan *et al.* 1987), and by others working on wayfinding and navigation (Gopal *et al.* 1989, Golledge *et al.* 1993). By the late 1980s, this thread was being related to other aspects of cognitive studies of geographical space and process.

2.7. *COSIT: Conferences on Spatial Information Theory*

The development of a series of conferences with refereed proceedings, under the name 'Conference on Spatial Information Theory' (COSIT), was an important factor in the development of a community and field of study in cognitive foundations of geographical information science, and the maturation of the field. The COSIT meetings grew out of a series of workshops, NATO Advanced Study Institutes (Mark and Frank 1991), and NSF-sponsored specialist meetings concerned with cognitive and applied aspects of representing large-scale space, particularly geographical space. In these meetings, the need for a well-founded theory on spatial information processing was identified. The conference series was established in 1993 as an interdisciplinary biannual European conference on the representation and processing of information about large scale (geographical) space after a successful international conference on the topic had been organized by Andrew Frank and others in Pisa in 1992 (Frank *et al.* 1992). The 1992 Pisa meeting has subsequently been informally referred to as 'COSIT zero'. After two successful European COSIT conferences (COSIT'93, Elba, Italy, Frank and Campari 1993; and COSIT'95, Semmering, Austria, Frank and Kuhn 1995), the conference became a truly international enterprise when COSIT'97 was held in the United States (Hirtle and Frank 1997). COSIT'99 is scheduled to take place in Germany. COSIT brings together researchers and methodologies in the area of spatial information theory from different disciplines, in particular: Geography, Geodesy, and Geo-information Science; Computer Science and Artificial Intelligence; Cognitive Science; Cognitive and Environmental Psychology; Architecture and Environmental Design; Cognitive Anthropology and Psycholinguistics; and Philosophy of Mind. COSIT covers theoretical implications of empirical investigations, formal models, applications, and spatial information technology, and the community of like-minded scholars that participates in the COSIT meetings is evidence of a coherent field of study at the interface between cognitive science and geographical information science.

2.8. *Summary*

Much of the research reviewed in this section was not conducted in the framework of geographical information systems or geographical information science, or even in the context of computation. However, these research themes and communities are critical input to computational theories of geographical cognition, and to formal models of geographical space, phenomena, and features that contribute to the foundations of geographical information science.

3. Major current research themes

Clearly, a multidisciplinary effort is required to develop and validate cognitive models for geographical space that are compatible with computation and that can form part of the theoretical grounding of GIS. The fields of geography and cartography provide concepts and relations for geographical space. Cognitive and environmental psychology provide empirical investigations and models of human factors. Artificial intelligence provides formalizations and computational models, as well as ontologies and structures for the development of cognitive models. Linguistics provides a link to the construction of descriptive spatial phrases and the use of spatial metaphors. Philosophy provides a theoretical foundation for spatial concepts.

In this section we review major research themes in cognitive geography and geographical cognition, not by disciplinary perspective or research methods, but by stages in a hypothetical information flow model for spatial and geographical cognition.

3.1. *Acquisition of geographical knowledge*

For humans, knowledge of space is acquired in many different ways. Although the prototypic experience may be actual exploration, by the time children are talking, telling them where to find the cookies may be all that is needed. Still older children can and do use maps for finding their way. Actual exploration itself is complex. There is good evidence that visual information about space has different qualities from kinesthetic and vestibular information, and that both differ from acoustic or tactile information (e.g. Loomis *et al.* 1993, Berthoz *et al.* 1995). For example, updating orientation changes is more accurate following sightless real movement than imagined movement. Characterizing the kind of spatial information imparted by each modality and describing how they are integrated in actual behaviour are topics ripe for investigation. Despite their differences, all of these modalities provide valid and often substitutable information about space, although the embodied information is more important for local guided navigation, and the cognitive for judgements in larger-scale space.

The process of extracting geographical knowledge from locomotion through a space requires a series of complex interactions. As Montello (1997) argues, the conversion of sensorimotor information into geographical knowledge is an indirect process, in which environmental features are used to generate spatial characteristics, such as distance information. Such environmental features include not only physical characteristics, such as turns, landmarks, intersections, and barriers, but also travel time, travel effort, and aesthetic qualities of the space. Such characteristics are often visually acquired, but might also be acquired through other modalities. Virtual reality (VR) provides an alternative spatio–temporal experience for locomotion, which can mimic some of the complexities of movement through space (Berendt and Jansen-Osmann 1997), but may not provide a full sensory experience to the traveller. Geographical information systems themselves also provide ways to learn unfamiliar spaces and reason about geographical phenomena. Subtle differences provided by perceptual texture gradients or kinesthetic variations in surface qualities are often lacking in VR simulations, and current GISs certainly do not provide direct transperceptual experiences, but often are closer to an interactive version of map use.

Alternative media for acquisition often focus on the schematization of geographical knowledge for improving communication efficiency. This might include the use of maps (Head 1991), descriptions in natural language (Taylor and Tversky 1992), or spatial abstractions, such as data charts or other visualization techniques (MacEachren 1995, Tversky, in press). The ability to construct mental models from text is an essential component to the understanding of narrative stories (Morrow *et al.* 1987). Furthermore, spatial mental models constructed from text are similar in content to those constructed by studying maps of same scene in terms of generic spatial knowledge (Taylor and Tversky 1992, Federico and Franklin 1997). However, geographical information acquired from pictorial input appears to be retained longer than similar information obtained from text (Federico and Franklin 1997).

For over two decades, the acquisition of spatial knowledge has been modelled by the continuum of landmark, route, and survey knowledge (Siegel and White 1975). This trichotomy, while once assumed to be acquired in a strict ordinal fashion, is now believed to be acquired, at least partially, in parallel in many situations (Thorndyke and Hayes-Roth 1982, Hirtle and Hudson 1991). Route information is gleaned in parallel with identification of landmarks (Presson and Montello 1988), and survey information is constructed in parallel with building routes when possible (Moar and Carleton 1982).

It is important not to minimize the linkage between the environment and the representational schemes that are used to navigate through it. As Hutchins (1995) argued, the environment provides a context for learning with constant feedback and adjustment. Learning, according to Hutchins, is the adaptive reorganization in a complex system which includes the environment and communication among actors in that environment. Edwards (1997) argues for a combination of cognitive and geometric approaches, in which two representational structures, views and trajectories, provide the basic building blocks of spatial, his framework, which he calls geocognostics, provides a model for understanding the biases that are inherent in the learning and use of GIS, among other applications. This is but one of several models that combine views and trajectories.

3.2. *Mental representations of geographical knowledge*

Any behavioural expression of spatial knowledge requires both knowledge representation and knowledge retrieval. Separating the contributions of representation and retrieval is difficult, if not impossible. Converging evidence from different retrieval tasks strengthens the case that effects are due to knowledge representation. Even so, because different knowledge is retrieved for different tasks, knowledge representations of space are probably not best conceived of as coherent, unchanging wholes, but rather as conglomerations of information drawn from different sources and modalities and pulled together for a particular purpose.

With those provisos in mind, can spatial knowledge be characterized in any general ways? Several metaphors have been proposed for representation and processing of geographical knowledge: the cognitive map, the cognitive atlas, and the cognitive collage. To most psychologists at least, the term ‘cognitive map’ has connotations of metric properties, like a drafted, cartographic map. This conception comes mostly from Kosslyn’s work on imagery, which has argued that images are like internalized perceptions and quite true to what is seen (Kosslyn 1980). ‘Cognitive atlas’ was introduced by Kuipers (1982) as a term to refer to a collection of cognitive maps, perhaps of different scales, and with gaps. Tversky (1993) introduced the term 'cognitive collage' to emphasize the fact that mental representations driving judgements and wayfinding are fragmented, partial, constructed, and multi-media.

There seems to be ample evidence that spatial knowledge does not have the metric qualities that maps do. As noted earlier, geographical space, though locally flat, is organized hierarchically, both in cognition and in administrative practice (Stevens and Coupe 1978, Maki 1981, Chase 1983, Allen and Kirasic 1985, Hirtle and Jonides 1985, McNamara 1986). Spatial information is organized by geographical boundaries, by economic categories, and by functional groupings of all kinds. The consequences of imposing hierarchical structure are that distances within categories are judged to be smaller than distances between categories (Hirtle and Jonides 1985), that direction judgements between categories are faster than those within (Wilton 1979, Maki 1981), and that directions of elements within a unit are distorted to the directions of the encompassing unit (Stevens and Coupe 1978, Tversky 1981).

Geographical elements, then, are organized as parts of larger geographical units. That hierarchical organization affects distance and direction judgements. Geographical elements are also organized one to another. When one of the elements is a better landmark, then that organization is asymmetric. Ordinary elements are judged to be closer to landmarks than landmarks to ordinary elements, violating usual metric conventions (Sadalla *et al.* 1980, McNamara and Diwadkar 1997). When the geographical elements are more or less comparable, such as North and South America, then they are organized together and remembered as more aligned geographically than they actually are (Tversky 1981).

In retrieving the relevant geographical information to make a judgement, people may take a particular perspective on the set of information. The perspective, too, can alter judgements. Holyoak and Mah (1982) found that people judged distances between pairs of near cities to be larger relative to pairs of distant cities, where near and distant were determined by an imagined east- or west-coast perspective.

The arrangement of the physical environment as experienced is also known to affect distance judgements, specifically, the amount of clutter or the number of intersections and nodes or the presence of barriers. On the whole, these increase distance estimates, but often reversals are obtained (Sadalla and Magel 1980, Sadalla and Staplin 1980a, b, Thorndyke 1981, Newcombe and Liben 1982). Irregular environments are remembered as more regular; for example, streets and rivers as straighter (Milgram and Jodelet 1976, Chase and Chi 1981) or more parallel or perpendicular than they actually are (Golledge and Spector 1978, Byme 1979, Tversky 1981, Moar and Bower 1983).

These are only some of the ways that people's knowledge of the geographical world differs systematically from the actual geographical world. Together, these findings suggest that mental representations of the geographical world are not stable, map-like entities that can be consulted as maps can be viewed. Rather, they seem to be constructed for a particular goal, drawing from the multiple sources of scattered information available those bits of information that seem relevant. Mental representations of geographical information seem to be constructed from elements, such as roads, landmarks, cities, land masses, the spatial relations among them, and the spatial relations of them to the larger units encompassing them. This schematization of the geographical world provides a framework for integrating information from different sources, modalities, and occasions. Like all schematizations, it also simplifies the complex and categorizes the continuous, allowing distortions as well as integration (Tversky 1992, Tversky and Lee 1998).

3.3. *Knowledge use*

Not only are the sources of knowledge of space diverse, but the uses to which that knowledge is put are similarly varied. The prototypical use is finding one's way, but spatial knowledge is also used to make geographical judgements, such as estimates of distance and direction. Indeed, wayfinding seems to require implicit if not explicit judgements of distance and direction.

McDermott and Davis (1984) developed an artificial intelligence model for planning routes through uncertain territory. In their system, topological and imprecise metric information is represented and used for selecting a promising path towards a given goal. Route planning is modelled as a process of finding the overall direction and topology of the path, then filling in the details by deciding how to go around barriers.

Towards the end of the 1980s researchers from different disciplines independently developed formal and computational approaches for representing and processing knowledge about large-scale space. While Egenhofer's (1989) and Frank's (1991) work was directly driven by issues in geographical reasoning, the approaches of Mukerjee and Joe (1990), Freksa (1991a, b, 1992, Freksa and Zimmermann 1992, Zimmermann and Freksa 1993, 1996, Schlieder (1993), Hernandez (1994) and Freksa and Barkowsky (1996) were largely motivated by cognitive considerations independent of specific applications. The work of Cohn and co-workers (Guesgen 1989, Cohn *et al.* 1993), Ligozat (1994) and Faltings (1995) has its roots in formal (logic-based, geometric, topologic) concepts while Jungert's work on navigation (Jungert 1988) grew out of database-oriented research concerned with encoding pictorial information.

Despite these differences of concern, the approaches converge remarkably with respect to some basic issues. The approaches have in common that they employ *qualitative* rather than *quantitative* information. Most of them are strongly related to Allen's work on qualitative *temporal* reasoning (Allen 1983, Freksa 1992). While temporal reasoning is concerned with one dimension only (the time axis), spatial reasoning deals with orientation information in addition to distance information. As it became evident that these independently developed approaches have much in common (Freksa and Röhrig 1993) and are suited to complement one another (Röhrig 1998), the European research network *Spacenet* was formed to promote interaction and exchange between the different perspectives and approaches. A recent overview by Cohn (1997) covers qualitative spatial representation and reasoning techniques.

Reasoning about large-scale space is relevant not only to immediate applications in geography, but also is particularly relevant to robot navigation (Kuipers and Levitt 1988) and to human navigation in virtual environments (May *et al.* 1995). The comparison between human navigation performance in real and in virtual environments can provide important insights into the underlying cognitive mechanisms (Mallot *et al.* 1998)

Orientation and navigation performance can be effectively enhanced through geographical maps. The cognitive processes involved in representing knowledge in maps and in map reading therefore are of particular interest for studying the use of geographical knowledge. Cartographic research about the use of maps as media for representing spatial knowledge (McEachren 1995) is supplemented by formal studies describing cognitive processes involved in extracting and combining knowledge from maps to draw inferences useful for identifying geographical landmarks and routes

(Barkowsky and Freksa 1997, Berendt *et al.* 1998). It is still a topic of investigation to determine under which circumstances spatial, functional, or featural aspects are most heavily used in solving particular tasks. The German Science Foundation (Deutsche Forschungsgemeinschaft) supports a 6-year priority program for interdisciplinary basic research on spatial cognition (Freksa *et al.* 1998).

Maps can be viewed as special diagrams specifically designed for representing geographical knowledge about spatial regions. Diagrammatic reasoning research therefore provides important foundations for the analysis and synthesis of spatial reasoning in geographical contexts. Diagrammatic reasoning is one of the early research areas in artificial intelligence; Glasgow *et al.* (1995) published an excellent collection of important contributions to the field.

3.4. *Communication of geographical information*

Besides viewing maps as vehicles for performing spatial inferences, they can be studied as a means of communicating spatial knowledge. Thus the topic of generating sketch maps for the purpose of describing places or routes or for complementing verbal descriptions of space is of interest (Tappe and Habel 1998). One ancient and reliable means of conveying geographical information is a map. Useful maps, like other useful graphics, are not simply reductions in size of actual worlds; rather, useful maps extract the essential information and eliminate the inessential (Tversky, in press) Of course, what is essential and what is inessential depends on the goals of the user. The schematization of graphics often parallels the schematization of the mind.

Yet another way to convey spatial information is through language, also a venerable way to communicate about space. Useful analyses of the connections between language and space appear in many of the papers in Bloom *et al.* (1996) as well as a paper by Landau and Jackendoff (1993). Spatial expressions typically describe a target or figural object in relation to a background object (Talmy 1983), as in 'the church is west of the town hall'. Languages typically have several different reference systems for describing spatial relations. 'West of' uses an extrinsic (also called geocentric or environmental) reference system. An expression like 'the church is left of the town hall' is ambiguous in English, using either a relative or intrinsic reference system. According to Levinson (1996), a relative reference system is centred on a viewer and uses a three-term relation: the church is in front of the town hall from the viewer's perspective. An intrinsic reference system is a two-term relation projected from the intrinsic sides of an object (or person). In this case, the church is in front of the front of the town hall. Neuropsychological evidence indicates that locations are perceived according to all three (and maybe more) reference systems (Behrmann and Tipper 1998).

What perspective is used for description depends on a number of variables. There are some languages that do not use the relative reference frame, using an extrinsic reference frame instead (Levinson 1996). For languages that use all three reference systems, the relative frame seems to be used primarily for environments that can be viewed from a single point (Ullmer-Ehrich 1982, Taylor and Tversky 1996). For larger environments that cannot be seen from a single viewpoint, people's descriptions use both extrinsic reference frames as in survey descriptions and intrinsic reference frames with a person as the central reference object as in route descriptions (Taylor and Tversky 1996). Quite frequently, people switch perspective, usually without signalling. When environments have features on several size scales and contain many alternative routes, there is a shift in preference toward more survey descriptions.

An additional issue arises in two-person interactions. Whose perspective do speakers adopt, their own or that of their addressees? Schober (1993) found that in the majority of cases, speakers take the perspectives of their addressees, and that this tendency was even more pronounced in cases where the addressees were unknown. In a variation of Schober's task, Mainwaring *et al.* (unpublished) also found that both American and Japanese speakers preferred their addressees' perspectives. They attributed this to considerations of relative cognitive load rather than politeness as variations in cognitive load led to variations in perspective.

In face-to-face communication, gesture as well as words convey spatial location. Emmorey *et al.* (in preparation) found that the oral component alone of videotaped descriptions was not sufficient for conveying the environment; the gestures in many cases supplemented and disambiguated the verbal information. Many of the accompanying gestures were iconic; for example, gestures indicating turns and intersections. Gestures accompanying spatial descriptions are in many cases language-specific, following language-specific schematizations of space (Kita *et al.* in press).

Route directions are of particular interest as an aid to wayfinding. In his analysis of a large corpus of route descriptions, Denis (1997) found two types of statements: references to landmarks and prescriptions of actions. Route directions can be segmented by actions that use landmarks as referents. In another set of studies, judges rated spontaneous directions for quality. Those rated as good followed the structure proposed by Denis (1997). Travellers using the highly rated directions were more likely to find their way in Venice than travellers using poorly rated directions (Denis *et al.* 1998). Sketch maps are also a good tool for wayfinding, and, in fact, schematize routes in much the same way as verbal directions (Tversky and Lee 1998).

4. High priority cognitive research within the Varenius project

The Varenius project (Kemp *et al.* 1997) is organized around three main topical areas in GI Science, one of which is cognitive models of geographical space. Each topic area is directed by a panel of five individuals, and the authors of this paper make up the cognitive panel. Each panel has identified several important topics for further research, and has ranked them in order to select three topics that became Varenius research initiatives and the subjects for workshops. In this section, we review the three researchable topics that were identified by the Varenius project as the cognitive topics of highest priority. We also review other identified topics that, while worthwhile, were considered lower in priority. Research initiatives begin with Specialist Meetings, which are workshops that bring together 30–40 researchers from a wide range of disciplinary perspectives to provide detailed priorities for researching the topic. Such meetings were conducted for each of the following three topics between May 1998 and February 1999.

4.1. *Formal concepts of geographical detail*

Degree of geographical detail is one of the most poorly understood and most confusing of the fundamental geographical concepts that underlie our cognition of geographical objects, spaces, and phenomena (Montello 1993). Scale, although often used ambiguously and poorly defined, is nevertheless an important component of naive geography, which asserts that geographical scales are different in fundamental yet unspecified ways from things at other scales (Egenhofer and Mark 1995b). If this is so, do certain spatial processes suddenly come into existence at some specific scale? Are they not present at micro-levels (larger scales)? Do all spatial processes have an emergence threshold, or are spatial and geographical processes really scale invariant but ignored as larger and larger scales (i.e. smaller and smaller areas) are examined? How do we rationalize the different uses of the term (e.g. in cartography, compared to in environmental modelling)? Is scale more important in the physical domain than in the human? Are spatial cognitive processes scale-dependent? What scales of representation lend themselves most to visualization, and to other forms of representation? How does a scale change influence granularity or clarity of data? Does a change in scale involve loss of original structure and emergence of artificial structure or patterns? To what extent is scale at the crux of traditional geographical arguments of form versus process? Does scale change involve changing models? How do visual representations of spatial phenomena need to change with a change in scale? While GIS and other automated cartographic systems allow rapid changes of display scale, they do not take into account the perceptual requirements of the viewer. Do the perceptual requirements of the viewer change along with a change in scale, or are they constant across many scales? What types of data are most amenable to display at multiple scales? How should those data be manipulated when scale changes, through cartographic generalization? All of these questions are important to this research initiative.

As society makes the transition to digital worlds, associated metaphors for geographical detail are likely to change also. Metric scale or representative fraction, the measure of geographical detail dominant in the cartographic world, has no well-defined meaning in a digital world of seamless perspectives on geography in which the user is free to zoom and pan at will. Other metaphors, such as the view from space, may replace metric scale with less familiar dimensions such as the distance of the viewpoint from Earth, as they do in Microsoft's Encarta Atlas. This suggests two fundamental objectives for this initiative, in addition to those identified earlier: (1) can we identify the fundamental, invariant dimensions of the concept of geographical detail that survive the transition from analogue to digital, and (2) can we identify the mapping between these dimensions and the terms and metaphors commonly used in naive geography? The initiative on 'Formal Concepts of Geographical Detail' is led by Daniel Montello and Reginald Golledge, both of the University of California, Santa Barbara, and its Specialist Meeting was held in Santa Barbara in May of 1998.

4.2. *Cognition of dynamic phenomena and their representations*

The ability to manipulate, interpret, and store information about changing environments is a critical human survival skill, and also is very important for geographical information science. Models of the cognitive aspects of dynamic spatial representations are necessary for understanding temporal and spatial changes in spaces or maps, for the manipulation of temporal geographical data, and for navigation through changing spaces. Furthermore, the use of representational information may be dependent on the context of the problem, with different entity types resulting in the adoption of different spatial metaphors for reasoning and understanding. For example, land use changes might be viewed as changes in attributes of a fixed location, whereas an advancing forest fire is thought of as a moving entity of change shape and size. And, at a different temporal scale, the former process, involving no real motion, might be talked and reasoned about as the spread or sprawl of development. Some other examples of dynamic geographical processes include navigation through changed environments, diffusion of diseases, and much slower processes such as glaciations, mountain-building episodes, or continental drift and plate tectonics. At a database level, we are concerned with issues such as forming discrete representations of continuous phenomena or continuous representations of discrete phenomena. Cartographically, the emphasis is on animation, but many methods have been used to show temporal phenomena on static maps. The use of dynamic and manipulative interfaces also must be investigated within the same conceptual framework used for observing dynamic phenomena in the real world.

The Varenius research initiative on 'Cognition of Dynamic Phenomena and their Representations' is led by Stephen Hirtle of the University of Pittsburgh and Alan MacEachren of the Pennsylvania State University. The initiative takes a dual and parallel look at dynamic phenomena in geographical space itself, and at their representation in dynamic displays of geographical information. If research finds that there are systematic differences in human cognitive responses to various kinds of change and motion in geographical space, then different representations may be appropriate for the different situations. If different kinds of computer displays also trigger different kinds of human memory, reasoning, or decision-making, then the match between cognitive models for the phenomenon being represented and those for the display methods will influence how intuitive and usable the display will be. This research initiative held its Specialist Meeting in Pennsylvania in October of 1998.

4.3. *Multiple modes and multiple frames of reference for spatial knowledge*

Space can be experienced directly, through vision, hearing, touch, and other modalities, as well as indirectly, primarily through language. Space can be viewed from many different perspectives, and conceived of from perspectives that have not or cannot be viewed. How do people interact with multiple modalities and multiple frames of reference? How do they integrate and reconcile the varied information, if and when they do? What are the relative advantages and disadvantages of each kind or source of spatial information? These are issues that have arisen in linguistics, philosophy, computer science, anthropology, and psychology, as well as in geography, in theoretical as well as applied contexts. However, there are many open questions, especially with respect to human behavior and learning in natural situations. Understanding how people combine or juggle information from a variety of sources in a variety of forms is important to geographical information science and GIS in at least two ways. First, it is important in deciding how to provide additional information to system users, dependent in part upon what they already know. Second, the ways in which people represent and combine geographical information may help in the design of computerized systems to do the same thing.

Some specific topics serve as examples: relative, intrinsic, and absolute reference frames for describing locations; heads-up and north-up maps in navigation systems; mixing gaze, route, and survey perspectives in descriptions; tactile, auditory, visual localization; orientation-free vs. orientation-specific representations; expressing differing modalities or frames through language; and cross-cultural differences in the use of reference frames. The Varenius initiative on 'Multiple Modes and Multiple Frames of Reference for Spatial Knowledge' is led by Scott M. Freundschuh of the University of Minnesota, Duluth, and Holly Taylor of Tufts University, and the Specialist Meeting was held in Santa Barbara in February of 1999.

4.4. *Other topics*

The Varenius project panel on cognitive models of geographical space identified several other cognitive research topics that, while not considered quite as important as the three detailed above, were still thought to be worthy of research attention. In this section, we give brief overviews of several of these topics.

(a) Ontology of geographical entities. Categories are central to human cognition. Psychologists and other cognitive scientists have developed a well-established model of the nature of categories. The model, grounded in the work of Eleanor Rosch (1973, 1978) and reviewed in depth by Lakoff (1987), has shown that, while cognitive categories are often like mathematical sets, they frequently depart from classical set theory in important ways, having consensus best examples, internal structure, and indistinct category boundaries. Mark (1993) discussed how this model of categories might provide a theoretical foundation for definition of entity types in geospatial information transfer standards such as the US Spatial Data Transfer Standard (Fegeas *et al.* 1992). The above theory of cognitive categories is well-established and widely accepted. However, it is based almost entirely on studies of categorizations of biological entities, artefacts, and other manipulable objects. Recently, Smith and Mark (1998) provided evidence that geographical objects are different in fundamental (ontological) ways from the sorts of objects studied by Rosch and her colleagues and followers, and suggested that category formation might be different here also. A research initiative on this topic would focus on the nature of basic-level categories of geographical entities, and their role in geographical cognition. The committee recognized this as a very important topic in its foundational role in geographical information science. They also felt, however, that the researchable questions, as well as the methods to be used in investigating it, were well established in psychology. Thus this topic is a good candidate for research, but probably would not benefit as much from a workshop as would some of the other topics discussed and described above, where the approach to doing the research, and the priority subtopics, are less well defined.

(b) Mental maps. The entire area of geographical knowledge at an individual level, or mental maps and related topics, is important. Research questions include the ways in which knowledge of geographical space is represented in the brain, how it is recalled, how people reason to derive new knowledge, and what are the relative roles of different sources of geographical information. Are there important differences due to scale? Is geographical information represented differently depending on its source, when it is learned from maps versus learned from text versus learned from real-world experience? Are there important cultural or sex-related differences in the answers to the above questions? Although these are critical topics with more research needed, there already is a considerable literature on the topic, and an active research community. The probable marginal effect of a Varenius project initiative on mental maps on progress in this area was not judged to be as great as the probable effect on research progress of the three highest priority topics described above. Lastly, it is a very broad topic, and the topics addressed by the initiatives on detail and reference frames and modalities will contribute to understanding of mental maps.

(c) Formalizing spatial relations. Spatial relations are one of the most distinctive aspects of spatial or geographical information, and thus a better understanding of the cognitive aspects of spatial relations, and their formalization in computational

models, is critical to the advancement of geographical information science. As with some of the other topics discussed above, these is an active research community and research literature on spatial relations which has momentum independent of the Varenius project (for example, see Mark and Egenhofer 1994a, b, 1995, Egenhofer and Mark 1995a, Mark *et al.* 1995, Shariff *et al.* 1998), and thus the probable impact of a Varenius initiative on progress in formalizing spatial relations was not thought to be as high as for some of the other topics.

(d) Additional topics. Six other topics were identified by the panel on Cognitive Models of Geographical Space as being of some potential interest and importance. These are less well-defined than the topics outlined earlier in this section, and are listed here for completeness and to alert readers to topics in need of attention by the research community.

One of these is the issue of place—what are the cognitive models of place and neighbourhood, and can these be implemented in computational environments? What would a place-based, rather than coordinate-based GIS look like, and what could it do, and not do? Another topic would examine navigation in virtual spaces: how similar is this to navigation in real spaces, and how can the look and feel of virtual spaces be designed to maximize navigability? Another topic would address issues in the design of graphic displays and diagrammatic reasoning. This topic may be too far away from geographical information science, since it deals with diagrams as diagrams rather than as representations of geographical spaces. Some aspects of this topic are covered under the Varenius initiative on Cognition of Dynamic Phenomena and their Representations. The panel also felt that the role of experience in the ability to use displays was worthy of some attention from researchers, but arguments against giving it high priority are similar to those just presented for diagrammatic reasoning. Another topic would be to study the design and implementation of cognitive agents for GIS. This is somewhat related to the knowledge discovery initiative under the computational models panel of the Varenius project. Lastly, the very broad topic of the semantics and structure of geographical space was raised as an important goal.

5. Conclusion and prospects

In this paper, we have reviewed research in geographical cognition that provides part of the theoretical foundation of geographical information science. Free-standing research streams in cognitive science, behavioural geography, and cartography converged in the last decade or so with work on theoretical foundations for geographical information systems to produce a coherent research community that advances geographical information science, GIS, and the contributing fields and disciplines. The Internet is now delivering albeit simple GIS functions to the general public, and systems for use by untrained people provide new challenges for systems designers. Many of those challenges relate to the cognitive models of geographical space and phenomena that are held by members of the public (Egenhofer and Mark 1995b, Mark and Egenhofer 1996). Cognition by spatially-aware professionals and other experts must not be ignored.

Emerging geographical technologies such as Global Positioning System (GPS) receivers and wireless information systems also provide cognitive research challenges for GIScience. Can virtual scenes be superimposed on the real world in such a way as to augment the geographical information available to people in the field? What are the cognitive implications of such systems, and how can knowledge of principles of human cognition of geographical spaces inform the design of augmented reality systems and other forms of geographical field computing?

There are also basic research challenges that lie in the nature of geographical cognition itself. How exactly does the relative size of objects or spaces influence how they are cognized, if it does at all? If geographical cognition is different from spatial cognition at other scales, is the difference somehow indexed to the size and physical capabilities of the human body? How many of the differences between CAD (computer-assisted design) and GIS software result from the differences in how their application domains are dealt with in human cognition, and can formalized knowledge of the exact ways that geographical and non-geographical spatial cognition differ be used to make better and more easily used software? Studies of geographical cognition, and of computational models based on findings of such studies, will continue to be an important basis for geographical information science.

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