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CHAPTER THREE

Cognition of Geographic Information

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3.1 INTRODUCTION

"Geographic information science" has newly emerged as the study of basic and applied research issues involving geospatial information. This multi-disciplinary field is concerned with the collection, storage, processing, analysis, and depiction and communication of digital information about spatiotemporal and thematic attributes of the earth, and the objects and events found there. One area of research within geographic information science involves the cognition of geographic information. Cognition of geographic information deals with human perception, memory, reasoning, problem-solving, and communication involving earth phenomena and their representation as geospatial information. Research in cognition is relevant to many issues involving geographic information: data collection and storage, graphic representation and interface design, spatial analysis, interoperability, decision-making, the societal context of geographic information systems (GIS), and more. We believe that many aspects of GIS usability, efficiency, and profitability can be improved by greater attention to cognitive research.

Research on geographic cognition is important to many areas of high priority within the national research and development agenda. An understanding of how humans conceptualize geographic features and information will help promote interoperability of systems, including distributed information systems. Good examples of this include attempts to develop national and international data standards, and attempts to create digital geographic libraries. Research on geographic cognition will improve the functionality and dissemination of many information technologies, including data capture technologies, GIS, and intelligent transportation systems. It will also help provide ways to externalize the divergent belief and value systems of different stakeholders in land use debates. Finally, the study of geographic information cognition will play a major role in improving the effecttiveness of geographic education at all levels.

Inadequate attention to cognitive issues impedes fulfillment of the potential of geographic information technologies to benefit society. Cognitive research will lead to improved systems that take advantage of an understanding of human geographic perception and conception, including that of spatial and geographic "experts". It will aid in the design of improved user interfaces and query languages. The possibility that it might lead to improvements in representations, operations, or data models is very real and should be investigated as well. In any case, a geographic information technology that is more responsive to human factors in its design will greatly improve the effectiveness and efficiency of GIS. In addition, cognitive research holds great promise for the advance of education in geography and geographic information at all levels. This includes both traditional general concerns about the poor state of geographic knowledge in the populace, and more specific concerns, such as education about the critical issues of global and environmental change, or extracting the concepts and approaches of geographic information experts.

To provide more equitable and effective access to GIS, it must be recognized that consumers of geographic information are not all the same. Some of these variations among individuals include differences in perceptual and cognitive styles, abilities, and preferences. Cognitive research will therefore allow us to respond to differences among users. Relatively inexperienced or disadvantaged users will gain access to geographic information technologies, and experienced or expert users will gain power and efficiency in their use of the technologies. Information access will be afforded to those with sensory disabilities, the young and the old, people from different cultures who speak different languages, the poor as well as the rich. Intelligent defaults and effective training programs will make systems accessible to the largest possible segment of the population. Alternatively, systems that are flexible may be customized to the particular needs of the individual.

A good example of the potential importance of cognitive research to geographic information science and technology is the development of the *Digital Earth*. Vice President Gore's speech introducing the concept of the Digital Earth was subtitled "Understanding Our Planet in the 21st Century." Understanding is a cognitive act. In the context of Digital Earth, it encompasses the knowledge we can acquire about the earth and its people with the help of new technologies. As such, a project like Digital Earth would only reach its optimal effectiveness with research on the cognition of geographic information. It may very well be an expensive and massive failure without this research. In addition to technology research on hardware and software development, we will need research on human cognition in order to improve the technology, making it help us understand the earth better, including ongoing natural and human processes. Cognitive research, as broadly construed in this chapter, will tell us what and how much information people want and can comprehend, and in what formats it should be presented. Research on the display and visualization of complex geographic information will be of crucial importance. The perception of patterns in space and time is a research issue of ongoing interest in the cognitive sciences. How do people integrate multiple sources of information presented in different sensory and representational modalities? In particular, how does this occur in immersive virtual environments, during a “magic carpet ride”? Digital Earth will allow rapid panning and zooming of displays to view places and landscapes at multiple resolutions, from the very large to the very small. It will also allow simultaneous views at multiple scales. Research on the comprehension and communication of scale and scale changes, in both space and time, will be needed in order to make this a reality. The development of an effective natural language interface for Digital Earth will require cognitive research on spatial and geographic language. Furthermore, it will be essential to understand ways that individuals and groups differ in their cognition of geographic information. Of particular importance, research on education, experience, and age differences will make it possible to build a system that can be used by the young and the old, the expert and the novice. Cognitive research will also help us develop the artificial intelligence components of Digital Earth, such as those involved in automatic imagery interpretation and intelligent data agents. In Mr. Gore’s words: “The hard part of taking advantage of this flood of geospatial information will be making sense of it—turning raw data into understandable information”. Research on the cognition of geographic information will play a central role in solving this difficult problem.

3.1.1 Background

A growing number of researchers are addressing cognitive questions about geographic information. Such work stems from a research tradition begun primarily in the 1950s and 1960s (with just a few pieces of work earlier) by behavioral geographers, cartographers, urban planners, and environmental psychologists. Behavioral geographers began developing theories and models of the human reasoning and decision-making involved in spatial behavior, such as migration, vacationing, and daily travel (Cox & Golledge, 1969; Golledge & Stimson, 1997). Geographers working in the area of “environmental perception” investtigated questions about human responses to natural hazards (White, 1945; Saarinen, 1966), including cognitive responses. Cartographers initiated research on how maps and map symbols are perceived and understood by map users, both expert and novice (Robinson, 1952). Finally, environmental psychologists joined planners and environmental perception researchers in refocusing traditional questions about psychological processes and structures to understand how they operate in built and natural environments, such as public buildings, neighborhoods, cities, and wilderness areas (Lynch, 1960; Appleyard, 1969).

During the decades since the 1960s, several additional disciplines within the behavioral and cognitive sciences have contributed their own research questions and methodologies to this topic. Within research psychology, the subfields of perceptual, cognitive, developmental, educational, industrial/organizational, and social psychology have all conducted research on questions relating to how humans acquire and use spatial and nonspatial information about the world.

Architects have joined planners in attempting to improve the design of built environments through an understanding of human cognition in and of those environments. Both linguists and anthropologists have conducted research on human language and conceptualization about space and place. Artificial intelligence (AI) researchers within computer science and other disciplines have developed simulations of spatial intelligence, in some cases as part of the design of mobile robots. Fundamental theoretical questions about alternative conceptualizations of space and place, and their representations in formal systems, have been investigated by mathematicians, computer scientists, and philosophers.

More recently, within the past 10 years, an interest in geographic cognition has developed within the geographic information science community, a community that now includes many of the disciplines described above. Several specialty groups of The Association of American Geographers are populated by researchers who concern themselves with questions at the intersection of cognition and geographic information, including Environmental Perception & Behavioral Geography, Cartography, GIS, Geography Education, Hazards, Disability, and Urban Geography Specialty Groups. GIS research labs are increasingly focusing on questions about the human comprehension of geographic information and the human factors of GIS (Medyckyj-Scott & Hearnshaw, 1993; Davies & Medyckyj-Scott, 1994, 1996; Nyerges, Mark, Laurini, & Egenhofer, 1995; Egenhofer & Golledge, 1998). The Conference on Spatial Information Theory (COSIT) has taken place every 2 years since 1993, bringing together researchers from several different countries and disciplines to discuss cognitive aspects of spatial information. The National Center for Geographic Information and Analysis (NCGIA) sponsored several workshops and research initiatives dealing with questions of human cognition; examples include I-2 on “Languages of Spatial Relations”, I-10 on “Spatio-temporal Reasoning”, and I-21 on “Formal Models of Common Sense Geographic Worlds.” In its recent incarnation as Project Varenius, the NCGIA’s research agenda was composed of three research panels. One of the panels was “Cognitive Models of Geographic Space”, comprised of three specialist topics: “Scale and Detail in the Cognition of Geographic Information”, “Cognition of Dynamic Phenomena and Their Representation”, and “Multiple Modes and Multiple Frames of Reference for Spatial Knowledge.” These meetings took place during 1998 and 1999; a summary may be found in Mark, Freksa, Hirtle, Lloyd, & Tversky (1999).

3.2 THEORETICAL PERSPECTIVES ON COGNITION

During the 20th century, several theoretical perspectives or frameworks have been developed in the study of cognition. These perspectives organize research, and provide competing and cooperating explanations for cognitive phenomena. One of the earliest was *constructivism*, emerging from the work of the experimental psychologist Bartlett (1932) and the child psychologist Piaget

(Piaget, 1926/1930; Piaget & Inhelder, 1948/1967). According to this perspective, knowledge of the earth and features on the earth is stored in the mind in the form of cognitive representations that are constructed from perceptual information combined with existing knowledge schemata that serve to organize the perceptual information. Earth knowledge is not simply a perceptual copy of the world but a construction that represents some properties accurately, and distorts or omits other properties. This perspective has been subsequently expressed in research on the structure, acquisition, and use of *cognitive maps*, reviewed below.

A clear alternative to the constructivist framework is the *ecological* perspective of J.J. Gibson (1950, 1979). Contrary to the dualist (according to Gibson) idea of constructivism, the ecological perspective asserts that knowledge exists in a mutual fit between organism and environment. Knowledge need not be constructed from perceptual input but is "directly" available in perceptual arrays encountered by moving organisms. These perceptual arrays are not collections of atomistic sensory properties (lights, tones, *etc*.), but meaningful higher-level units such as openings and support surfaces that provide information for the organism about functional properties of the environment, called *affordances*. More recently, the ecological approach has been mathematically developed by researchers working with "dynamic systems" theory (Thelen & Smith, 1994).

An *information-processing* perspective emerged in the late 1960s and 1970s. It agrees with the constructivist perspective that human cognition depends on the operation of internal representations, symbolic cognitive structures that model events and objects in the world. Unlike the constructivist perspective, however, internally represented information is not acquired in qualitative stages but is continuously and quantitatively built up over time. In addition to the structures that represent objects and events, the information-processing approach places emphasis on the roles of strategies and *metacognition* (cognition about cognition) that control the use of cognitive structures when reasoning about particular problems. An example is a person using a particular set of rules to perform a GIS procedure on several data layers. The information-processing approach is inspired by traditional rule-based digital computing, and is represented by work in formal/computational modeling and symbolic AI (*e.g.*, Newell & Simon, 1976). *Fuzzy logic* and *qualitative reasoning* have been influential within formal/computational modeling (*e.g.*, Zadeh, 1975).

Another perspective that, like the information-processing approach, has been popular with computational modelers is that of *connectionism* or *neural networks*. Stemming from Hebb's (1949) idea of *cell assemblies*, the connectionist perspective suggests that cognition operates by the activation of complexly interconnected networks of simple neuron-like nodes. The output of a network is determined by the patterns of interconnecting links, and weights on these links, that affect output from one node to another, essentially by increasing or decreasing the chances that a particular node will become active or not (Rumelhart & McClelland, 1986). These patterns change over time as a result of feedback into the network from the results of the network's previous outputs or the outputs of other networks. The connectionist perspective is thus thought to offer a model of cognition that does away with the need for the symbolic cognitive structures of the constructivist and information-processing perspectives. It is claimed to be a model of cognition that explicitly ties mental activity to the operation of the brain and nervous system, or at least a neurologically plausible model of the nervous system. Cognitive neuroscientists directly investigate the emergence of cognition in the brain and nervous system (Gazzaniga, 2000).

Throughout much of the 20th century, the importance of language as a vehicle of cognition has been stressed by researchers in anthropology, linguistics, and philosophy. During the 1980s, this *linguistic* perspective has been popularized and extended in the work of Johnson and Lakoff (Lakoff & Johnson, 1980; Lakoff, 1987), and linguists such as Jackendoff and Landau (1991), Levelt (1984), Levinson (1996), and Talmy (1983). According to this perspective, linguistic structures are the critical vehicles for human cognition. This points to the culturally variable nature of cognition insofar as people from different cultures speak different languages; as is well known by anyone attempting to translate ideas across languages, concepts in one language are only approximately similar to concepts in other languages. The “Whorfian Hypothesis” (among other names for this idea) states that language determines or at least influences the nature of cognition as it is practiced by members of different linguistic groups. According to “image-schemata” theory, language expresses meaning via the metaphorical extension of some modestly-sized set of *image schemata*, cognitive structures that capture essential concrete relations in the world in ways that allow their application to all meaning, including very abstract meaning. An example of this is the extension of the concept of a “path” connecting two places to any situation where entities are sequentially connected in time or space, such as the path through a computer menu system.

A sixth perspective that has recently become popular also stresses the role of culture, in particular the way that cognition takes place within a context of situations and artifacts partially determined by one’s culture. This is the perspective of *situated cognition*. Recently popularized in the English-language scientific literature, but originating early in the 20th century, Vygotsky (1934/1962) suggested that cognitive development is socially mediated and depends critically on language. More recently, others have popularized the insight that cognition serves to solve culturally-specific problems, and operates within contexts provided by culturally-specific problem-solving situations and task settings. Researchers such as Norman (1990) and Hutchins (1995) have stressed that cognition is actually embedded in structure provided by culturally-devised tools and technologies. Thus, it is incorrect, according to this perspective, to identify cognition as residing only in the brain or the mind. It also resides in the human body, the surrounds, and in what might be called “cognitive instruments.” A simple example is using one’s fingers to do arithmetic. A more complex example is the way a computer interface structures thinking and information processing.

Quite recently, a seventh perspective is gaining currency among some cognitive scientists. An *evolutionary* perspective takes issue with the information-processing and connectionist notions that the mind is a general purpose problem-solver. It also differs from the culturally-specific focus of the linguistic and situated-cognition perspectives. Instead, cognition is richly shaped by an innate cognitive architecture that has evolved over the hundreds of thousands of years of human biological evolution (Tooby & Cosmides, 1992). This architecture is posited to consist of several "domain-specific" modules that are specialized to solve certain classes of universally important cognitive problems. Good examples of such problems are finding a mate or finding one's way through the environment. Importantly, the evolutionary perspective suggests that humans from any cultural background will tend to reason in certain universal ways about particular problems. Advances in pedagogy or technology must be compatible with or must overcome these fundamental ways of knowing–compatible advances will work faster and more naturally for humans.

These seven major perspectives, and variations thereof, provide ample theoretical and conceptual raw material for interpreting past research on cognitive issues in geographic information science, and for providing directions for future research. Like theories in any developed science, empirical evidence provides support for some perspectives and argues against other perspectives. For example, the ecological notion that cognition is direct, without involving internally represented information in some form, is untenable if taken literally. Similarly, the mind as a general-purpose problem solver versus a collection of interconnected domain-specialized modules is hotly debated today. But it is no longer very reasonable to argue for the idea that the mind is a *tabula rasa*, whose structures and processes develop entirely from experience after conception, without some significant innate contributions. However, these multiple perspectives are not entirely contradictory by any means. To some degree, they simply focus on different aspects of cognition, perhaps on lower-level rather than higher-level components. A connectionist perspective, for instance, may be about the lower-level neural representations of symbolic structures favored by the information-processing approach. Similarly, whatever the nature of internally represented information, one can appreciate the fact that these representations derive in part from experiences in a particular culture and operate in particular situations where the environment provides information to solve problems. Although not the focus of most perspectives, few explicitly exclude the possibility of an innate architecture that guides and structures the operation of human cognition, as described by the evolutionary perspective.

3.3 LITERATURE REVIEW

3.3.1 Spatial and Environmental Cognition

Cognitive research about space and place has focused on several issues: the responses of sensory systems that pick up spatial information, the development of spatial knowledge from birth to adulthood (ontogenesis) and upon first exposure to a new place (microgenesis), the accuracy and precision of knowledge about distances and directions, spatial language, cognitive structures and processes used during navigation, and perceptual and cognitive issues in cartography, and very recently, GIS. With the advent of new technologies like GIS, new questions about spatial perception and cognition develop, and old questions (both basic and applied) become focused in new ways.

One of the most basic concepts in this area is that of the *cognitive map*. Introduced by Tolman (1948) in his work with rat spatial behavior, the cognitive map is a mental representation, or set of representations, of the spatial layout of the environment. According to Downs and Stea (1973), "cognitive mapping is a process composed of a series of psychological transformations by which an individual acquires, stores, recalls, and decodes information about the relative locations and attributes of phenomena in his [or her] everyday spatial environment" (p. 9). The cartographic map thus serves as a metaphor for spatial and environmental knowledge. Other metaphors have been offered as well, from topological schemata to cognitive collage (see Montello & Freundschuh, 1995). GIS and virtual reality provide our latest metaphors for environmental knowledge.

Cognitive researchers are interested in comparing various sources of geographical knowledge. Montello and Freundschuh (1995) review the characteristics of acquiring knowledge from direct environmental experience, static pictorial representations such as maps (see Thorndyke & Hayes-Roth, 1982), dynamic pictorial representations (movies, animations), and language (see Taylor & Tversky, 1992). Montello and Freundschuh listed eight factors that may play roles in differentiating these sources of geographic information: sensorimotor systems involved, static vs. dynamic information, sequential vs. simultaneous acquisition, the arbitrariness of symbols, the need for scale translations and their flexibility, viewing perspective, precision of presented information, and the inclusion of detail varying in relevance.

It is commonly thought that spatial knowledge of the environment consists of three types of features: knowledge of discrete landmarks, knowledge of routes that connect landmarks into travel sequences, and configurational or survey knowledge that coordinates and metrically scales routes and landmarks. In fact, inspired by Piagetian theory, it has often been suggested that these features represent a necessary learning sequence (Siegel & White, 1975; for an opposing view, see Montello, 1998). Landmarks in particular are thought to play an important role as anchor-points or reference points for the organization of environmental knowledge (Sadalla, Burroughs, & Staplin, 1980; Couclelis, Golledge, Gale, & Tobler, 1987).

Spatial cognition researchers have studied human navigation and orientation (Golledge, 1999). *Navigation* is coordinated and goal directed movement through space. It may be understood to consist of both locomotion and wayfinding processes. *Locomotion* refers to perceptual-motor coordination to the local surrounds, and includes activities such as moving towards visible targets and avoiding obstacles. *Wayfinding* refers to cognitive coordination to the distant environment, beyond direct sensorimotor access, and includes activities such as trip planning and route choice. Humans navigate and stay oriented both by recognizing landmarks (*piloting*) and by updating their sense of location via *dead reckoning* processes (Gallistel, 1990; Loomis, Klatzky, Golledge, & Philbeck, 1999). Some of these processes are relatively automatic (Rieser, Pick, Ashmead, & Garing, 1995), while others are more like conscious strategies (Cornell, Heth, & Rowat, 1992). A fundamental issue about human orientation concerns the systems of reference that people use to organize their spatial knowledge. Various possible systems have been discussed, including those that encode spatial relations with respect to the body, with respect to an external feature with or without differentiated appearance, or with respect to an abstract frame like latitude-longitude (Hart & Moore, 1973; Levinson, 1996). Several researchers have investigated reference systems within the context of verbal route directions (Allen, 1997).

A central effort in cognitive research on any task or skill domain, whether playing chess or solving calculus problems, is a characterization of the knowledge structures and processes involved in that domain. The same is true of research on spatial/environmental cognition. What is the nature of knowledge that results from exposure to environments or representations such as maps? How should we characterize the form or structure of that knowledge? What cognitive processes, such as encoding or image manipulation, are brought to bear on this knowledge during its use to navigate or give verbal directions?

Cognitive researchers have applied a variety of techniques to answering questions about the content of knowledge and how it may change with training and experience. Since the early 1970s, eye-movement studies have been conducted that record the direction and duration of the map reader’s gaze while viewing maps (summarized by Steinke, 1987). Perhaps a more direct research strategy for uncovering the content of knowledge is the use of memory tasks or protocol analysis (*e.g.*, Pick, Heinrichs, Montello, Smith, Sullivan, & Thompson, 1995). A common strategy for elucidating the form or structure of knowledge is to examine distortions or systematic biases in the performance of tasks involving the knowledge. One of the most striking findings in this area is the repeated demonstration that spatial knowledge is not stored simply as a “map in the head” which is read. The map metaphor is quite misleading in some ways (Kuipers, 1982; Tversky, 1992). Researchers interested in spatial knowledge structures and processes have noted the occurrence of systematic distortions in spatial knowledge. The cognitive map has holes, is compressed or enlarged in different areas, may fail to preserve metric information, and shows regularization effects. Spatial knowledge is stored in multiple formats, including spatial, mathematical, and linguistic structures. Nonpictorial cognitive structures (*i.e.* rules or heuristics) are used to organize one's knowledge of the environment, presumably because they decrease memory load and typically (but not always) support adaptive problem-solving.

Cognitive regionalization is an important example. The more or less continuous landscape is stored as discrete regions, and organized hierarchically, or at least partially so (Hirtle & Jonides, 1985; McNamara, 1992). Stevens and Coupe (1978) first suggested this with their finding that most people distorted the direction between San Diego, California and Reno, Nevada, indicating that Reno was east of San Diego (it is actually west). The authors attributed this to the notion that knowledge of city locations will be stored hierarchically within knowledge of state locations (California is mostly west of Nevada). Maki (1981) reached a similar conclusion from her response-time data showing that people were faster to identify the east-west relations of pairs of cities if they were in different states (see also McNamara, Hardy, & Hirtle, 1989).

Evidence for the operation of other simplifying heuristics for remembering spatial information has been gleaned from patterns of distortion. Tversky (1981) offered the heuristics of "rotation" and "alignment" to explain patterns of distortions she demonstrated. Both heuristics refer to phenomena wherein the remembered orientation or location of a feature learned from a map is distorted in order to more closely align the feature with another feature, or a feature and the global system provided by the cardinal directions. For instance, people typically underestimate how far north Europe is of the United States, instead remembering the two as being aligned with one another along the east-west dimension, and thus incorrectly answering questions about the relative north-south locations of cities in Europe and the United States (see also Mark, 1992). Recent work by Friedman and Brown (2000) suggests that these types of distortions in estimates of latitudes and longitudes ("psychological plate tectonics") are more conceptual than perceptual in origin. Their *plausible-reasoning approach* states that estimates will be based on a combination of multiple types of relevant knowledge, including prior beliefs, new information, and the context of the task. They demonstrated this in an interesting way by showing how estimates of the locations of world cities could be changed in systematic ways by providing subjects with "seed" locations for particular cities.

3.3.2 Cognition of Maps and Geographic Visualizations

One of the oldest areas of research in the cognition of geographic information is the study of cognitive and perceptual aspects of cartographic communication. Maps function to store and communicate information, and to support analysis and problem-solving with this information. Communication and problem-solving are, in part, mental and behavioral activities of individuals. Because maps are composed of sometimes complex systems of signs and symbols whose interpretation depends in profound ways on the prior knowledge and learning experiences of individuals, there are many interesting and subtle questions for researchers interested in the cognition of maps and map use (theoretical overviews may be found in Olson, 1979; Eastman, 1985; Blades & Spencer, 1986; MacEachren, 1992; Lloyd, 1993).

As a research topic, the cognition of maps has roots in the early 20th century. It began with a concern for map education (Gulliver, 1908; Ridgley, 1922), a concern that continues to this day (Blades & Spencer, 1986; Freundschuh, 1997). A second research focus on empirically evaluating and improving map design developed during the 1950s and 1960s. This body of work heralded the beginnings of what become known as *cognitive cartography*. Most of this research has dealt with questions about the perception of map symbols, such as graduated circles, legend symbols, and topographic relief symbols (for reviews, see Potash, 1977; Board, 1978; Castner, 1983). Petchenik (1983) provided an interesting and trenchant critique of this research enterprise. Among other points, she contrasted the analytic goals of research with the synthetic goals of mapmakers, and questioned the ability of research to accommodate the idiosyncratic nature of map users, map tasks, and map designs. Although Petchenik's critique probably moderated enthusiasm for map design research, the motivation to improve maps and map communication continues to inspire researchers (*e.g.*, Eley, 1987; Gilmartin & Shelton, 1989; MacEachren & Mistrick, 1992; Slocum & Egbert, 1993). But in the last couple decades, map-design research has been augmented with work that looks at reasoning and decision-making with maps. Here, we review two such areas—the effects of map orientation during use, and the cognitive development of map skills in children.

3.3.2.1 Map Orientation

Clear scientific evidence now confirms the intuitive understanding of many people that maps are easier or harder to use for tasks such as navigation if you orient them to face in particular directions. Maps are thus said to demonstrate *orientation specificity*: They are most accurately and quickly used when viewed in one specific orientation. If the map is turned to any other orientation, the increased errors and time involved in their use are known as *alignment effects*. When used during navigation, the most commonly preferred orientation for a map is with the top of the map being the direction one is facing in the world. This is variously called "track-up" or "forward-up" alignment. Levine and his colleagues (*e.g.*, Levine, Marchon, & Hanley, 1984) have convincingly demonstrated our preference for this orientation in the case of "you-are-here" (YAH) maps. Robust confusion results when using a YAH map whose top is not the direction one is looking when viewing the map. These researchers also documented the great frequency with which YAH maps in New York City are in fact designed (or placed) in such a misaligned way; it is likely that readers will find it easy to document this for themselves in their own hometowns.

Why does this alignment effect occur? It is clear that left and right on a properly oriented YAH map will directly correspond to left and right in the world, obviating the need for cognitively expensive mental rotation or manipulation. Furthermore, it may be relatively easy to metaphorically treat "forward" in the visual field as "up" on a map because the landscape does in fact "rise" in our visual fields as it stretches out in front of us (Shepard & Hurwitz, 1984). For most people, therefore, navigation maps will be easiest to use when they are oriented to the world in a track-up alignment. A more detailed discussion of map displays in In-Vehicle Navigation Systems is presented below.

However, maps are used for many other tasks than navigation. Thematic and statistical maps are used for scientific analysis, for example. Small-scale maps that depict large areas, such as world maps, are almost always used for purposes other than navigation. In these cases, the cognitive need for alignment with an immediate surrounds is no longer present. Instead, the preferred map orientation depends on learned conventions about how maps are designed and displayed, "north-up" in many cultures (*e.g.*, Evans & Pezdek, 1980). Some research with airplane pilots even indicates that a fixed alignment such as north-up is preferred by trained experts performing specialized and highly practiced navigation tasks (Aretz, 1991). But it bears emphasizing that while there are certainly instances in which track-up alignment is not preferred, research has consistently shown that maps are most easily used in a single preferred orientation for a given task. This fact is likely an instance of the importance of figural orientation in pictorial perception and cognition (Rock, 1974).

3.3.2.2 Education and Development of Map Cognition

The applied interest in map education mentioned above has been accompanied by a focus on basic-science questions about the development of children's map skills (Presson, 1982; Uttal 2000). One of the major cognitive abilities this research has highlighted is the ability to understand representational correspondence in maps, including the confusion sometimes surrounding iconic similarity (as when children believe a red line on the map is a red road in the world). These researchers have also considered the abilities required to understand the shift or rotation involved in interpreting oblique and vertical perspectives, and to use maps to perform planning and determine routes in the environment.

An intriguing debate has emerged about the development of map skills and the degree to which children are inherently equipped to understand maps. In brief, one side of the issue takes the position that young children's (ages 3–5) success at understanding aerial photographs and simple map-like representations indicates an inherent and "natural" ability to comprehend maps as semiotic systems (related claims are made by Landau, 1986; Blaut, 1991). The other side of the debate points to the empirical difficulties and confusions demonstrated by children attempting to understand maps, and takes Piagetian theories about the protracted development of spatial concepts as support for the notion that only rudimentary components of map skills are “natural” (Liben & Downs, 1989, 1993). In fact, this side argues, the full development of map skills is the result of specialized practice and training with maps over many years.

Although there is now agreement that young children can deal with map-like representations to an extent greater than was traditionally believed, and that early education with maps is desirable, the debate continues (Blaut, 1997; Liben & Downs, 1997). It appears that children must be exposed to a somewhat extended developmental and educational process to fully appreciate the more sophisticated significations of maps (such as contour lines). This point becomes most obvious when the complete diversity of map types and uses is recognized.

Liben (1997) presents a six-level, progressive typology for mastering external spatial representations such as maps “which begins with the straight-forward ability to respond to referential content depicted in presentations, and ends with the sophisticated ability to reflect upon the creation and utility of various kinds of representations” (p. 2). According to her model, children first identify the referential meaning of the representation, then the denotative meaning of the representation. Following that, children can distinguish between representation and referent, and intentionally attribute meaning to the representtation. Children then come to appreciate that some, but not all attributes of the representation are motivated by attributes of the referent, and that some, but not all attributes of the referent motivate graphic attributes of the representation. After that, children extend their prior understanding of attribute differentiation to develop understanding of the formal representation and geometric correspondences between representation and referent. Finally children are able to reflect upon the mechanisms by which, and the purposes for which, graphic representations are created.

Studying the early emergence of map skills helps clarify how adults use and understand cartographic displays. A developmental perspective seeks to shed light on the basic, core processes that are involved in map comprehension. A systematic comparison of adults and children of various ages should inform our understanding about what aspects of maps and spatial representations are relatively difficult to comprehend and which are relatively easy. A developmental perspective gives us a fuller appreciation of the difficulties adults have in understanding some of the more advanced map concepts, and what experiences promote such understanding.

3.3.2.3 From Maps to Gegraphic Visualizations

The traditional map is being supplemented by newer forms of geographic information displays, or geographic visualizations (MacEachren, 1995). These include various types of remote imagery, multivariate data displays, movies and animations, sound displays (sonifications), and virtual displays. In their review of psychological factors in remote sensing, for instance, Hoffman and Conway

(1989) discuss the issue of the best way to utilize color in graphic displays of imagery. A good example here is the custom of using red instead of green to represent lush vegetation, a practice that violates the natural expectations of novice viewers but is probably easily understood by experienced viewers. Other research questions involving imagery include feature search, the effects of clutter, and the interpretation of scale relations. Research on the effectiveness of geographic visualizations other than remotely-sensed imagery is ongoing as well. An example is Evans' (1997) work examining the effectiveness of dynamic displays of data uncertainty. Nelson and Gilmartin (1996) performed an evaluation of multivariate point symbols such as glyphs, Chernoff faces, and multivariate histograms. Monmonier (1992) has considered cognitive questions about the design of graphic scripts, which consist of dynamic sequences of maps, graphs, text, and other displays. These examples and other recent work like them only scratch the surface, however. Cognitive studies on geographic visualizations will clearly be a major focus of research for some time to come.

3.3.3 Geographic Ontologies: Entities, Features, and Concepts

Barring an extreme rejection of realism, it is safe to say that entities on the earth have an objective existence. However, identifying and labeling these entities is a construction of human mind and culture; the objective reality of earth features alone does not determine what people notice, remember, talk about, and theorize about. Both experts and lay people dissect the world into discrete entities, separating reality into classes, verbally labeling instances of these classes, and theorize about the formation and properties of these classes. The construction of *ontologies*, systems of concepts or classes of what exists in the world, is a cognitive act as well as a reflection of objective reality.

As a traditional branch of philosophy, ontology and epistemology make up metaphysics. Ontology deals with the question of the nature of that which exists; epistemology deals with the question of *how we know about* the nature of that which exists. There is recent work on geographical ontology in the traditional philosophical sense, including a nontraditional tendency to model the nature of what exists in formal or computational terms. A particularly interesting example is the attempt to model features or regions that have fuzzy or indeterminate boundaries (Burrough & Frank, 1996; Smith & Varzi, 1997).

To a cognitive scientist, however, ontology concerns the study of what exists according to the cognitive systems of intelligent beings. Thus, the cognitive approach combines traditional ontology and epistemology. There is a growing body of work on geographic ontologies in this sense. Perhaps the most straightforward is work that attempts to characterize the classes of features in the world that some community of people conceptualize as existing on the earth. If this community consists of lay people, their conceptualization of the earth and its features has been called naïve or commonsense geography (Egenhofer & Mark, 1995). An example might be the belief that the world is flat. Vosniadou and Brewer (1992) studied the development of commonsense understanding of the earth by children; Samarapungavan, Vosniadou, and Brewer (1996) extended this to the sun and moon ("commonsense cosmology"). At a more human scale, Tversky and Hemenway (1983) investigated the conceptual structure of environmental scenes.

The study of geographic ontologies is also concerned with the conceptualizations of experts or experienced geographic information scientists of various types. Hoffman and Pike (1995) claim that understanding how expert terrain analysts conceptualize topographic features will help us develop expert systems to perform automated terrain analysis. They developed the Terrain Analysis Database, a compendium of perceived and labeled terrain features, based on standard reference works on terrain analysis and an extensive interview with a leading aerial photo interpreter. Montello, Sullivan, and Pick (1994) analyzed the terrain features identified in environmental-scene and topographic-map recall tasks by experienced topographic map readers.

In the geographic information sciences, cognitive ontology might be quite important to GIS and remote sensing. Images are analyzed, areas of the earth's surface are grouped into regions, and discrete features are identified. Hoffman and Conway (1989) recognized that studying the way expert image interpreters identify land use categories is needed in order to more effectively automate image analysis. They discuss earlier work by Hoffman in 1984 in which think-aloud protocols of image interpreters were collected while they attempted to identify features on a radar image. Similarly, Hodgson (1998) did an experiment on the optimal window size for image classification. He provided a simple cognitive model for how humans classify land use/land cover categories (p. 798). Lloyd and his colleagues (Lloyd & Carbone, 1995; Lloyd, 1997) have investigated neural network models of categorization of geographic features, such as climate or land use categories. In the words of Hoffman and Conway: "Whenever an interpreter sits down in front of a computer graphic display or a set of satellite photos and maps, then perception, learning, and reasoning processes will all play a critical role" (p. 3).

Much of the work on the cognitive ontologies of geographic entities has been inspired by cognitive and linguistic category theory, in particular the notions of prototypes and basic-level categories (Rosch & Mervis, 1975; Peuquet, 1988). According to Usery (1993): "A geographical feature is an intellectual concept, and is established by selecting attributes and relationships relevant to a particular problem and disregarding characteristics considered to be irrelevant...selection based on a conceptual framework of basic objects in natural categories will maximize analytical utility and data transfer in feature-based GIS" (p. 8). Mark (1993) discussed the problem of cross-linguistic translation of geographic feature names such as lake and lagoon. The task of translating feature names is difficult because the categorical structure of apparently synonymous terms from different languages are not exactly the same. Gray (1997) also discussed the application of cognitive category theory to geographic information. An interesting application of Lakoff and Johnson's *image-schemata* to the problem of wayfinding in public spaces may be found in the work of Raubal, Egenhofer, Pfoser, and Tryfona (1997).

Work that applies *fuzzy logic* (Zadeh, 1975) is an important area related to cognitive category theory. Humans commonly use fuzzy concepts in order to communicate about the world. Unlike formal languages, natural languages used in everyday speaking and writing frequently refer to *ill-defined* categories and concepts that do not have precise referents and are not delimited by sharp semantic boundaries. Furthermore, and unlike formal concepts such as those of Euclidean geometry, exemplars of fuzzy natural language concepts vary in their degree of category membership—that is, they are probabilistic rather than deterministic (Smith & Medin, 1981; Lakoff, 1987). Researchers such as Wang (1994) and Wang & Hall (1996) believe fuzzy logic will allow the formal modeling of imprecise spatial language terms such as near and large, and fuzzy regions such as downtown; this modeling is necessary to develop automated systems that will allow GIS to communicate with people in natural languages such as English.

3.3.4 Formal and Computational Modeling of Geographic Cognition

Recently, researchers from several cognitive science disciplines have concentrated on developing and evaluating formal and computational models, both deterministic and stochastic, of geographic cognition. The neural network modeling of classification and category development discussed above is an example. Two additional approaches to formal/computational modeling have been especially active: (1) qualitative reasoning about spatial and temporal relations, and (2) formal models of cognitive mapping and navigation.

3.3.4.1 Qualitative Reasoning

One of the most active approaches in AI has been the development of *qualitative* models of cognition. Qualitative models represent spatial and temporal information using nonmetric or imprecise metric geometries. Generally, they also try to incorporate simple reasoning procedures rather than complex rules. For example, Egenhofer and Al-Taha (1992) present a model of topological relations between geographic features. The inspiration for qualitative modeling is the belief that it captures human cognition more faithfully than traditional quantitative models, and thus holds a key to modeling human spatial and temporal cognition. Qualitative modelers have noted several difficulties with information processing in the real world, including perceptual imprecision, temporal and memory limitations, the availability of only approximate or incomplete knowledge, and the need for rapid decision-making (Dutta, 1988). One of the attractive properties of such approaches is that they may provide a way to incorporate both the metric skills and metric limitations of human spatial behavior without positing separate metric and topological knowledge structures.

Models based on fuzzy logic (discussed in the Ontology section) provide an example of this approach. For instance, Dutta (1988) provides a fuzzy model of spatial knowledge in which a statement about distance and direction is modeled as two fuzzy categories, each category consisting of a center value, and left and right intervals of spread. The statement “object A is about 5 miles away”, for example, is modeled as having a center of 5 miles and 1 mile ranges around 5 miles. The statement essentially says that the distance is between 4 and 6 miles. The statement “object A is in a north-easterly direction” is modeled as having a center at 45° and 10° ranges around 45°. The statement essentially says that the direction is between 35° and 55°. In both cases, the correct value is modeled as having some nonzero probability of falling within the category range.

Probably most of the work on qualitative metrics has focused on knowledge of directions in the environment necessary for navigation and spatial communication. Although the details of these proposals vary, they agree in positing a model of directions which consists of a small number of coarse angular categories, commonly four 90° categories (front, back, left, right) or eight 45° categories (front, back, left, right, and the four intermediate). Frank (1991) provides good examples of such approaches. His models consist of either 4 or 8 “cones” or “half-planes” of direction. Values along the category boundaries are considered “too close to call” and result in no decision about direction. He also provides a set of operators for manipulating these values. Other writers provide similar models of directional knowledge (Freksa, 1992; Ligozat, 1993). Some models of qualitative distance exist as well (Fisher & Orf, 1991; Zimmerman, 1993). Allen and Hayes (1985) provide a very influential model of qualitative temporal reasoning.

3.3.4.2 Models of Cognitive Mapping and Navigation

Several disciplines have been involved in developing formal/computational models of cognitive mapping and navigation. Most attempts to model cognitive mapping and navigation have been carried out in the field of robotics. Some of the earliest and most influential work of this type is by Kuipers (1978, 2000). An extension and clarification of his TOUR model is described in his Spatial Semantic Hierarchy (SSH). It posits four distinct and somewhat separate representations or levels for knowledge of large-scale space; the four are simultaneously active in the cognitive map, according to Kuipers. The four are: (1) the Control level—this is grounded in sensorimotor interaction with the environment, and is best modeled in terms of partial differential equations that describe control laws specifying continuous relations between sensory inputs and motor outputs; (2) the Causal level—this is egocentric like the control level, but discrete, consisting of “views” defined by sensory experience and “actions” for moving from one view to the next. The views and actions are associated as schemas and are best modeled using 1st order logic; (3) the Topological level— this includes a representation of the external world, but only qualitatively, including places, paths, regions and their connectivity, order, containment. First order logic is appropriate here too; and (4) the Metrical level— this representation of the external world includes distance, direction, and shape to the topological level, as well as frames of reference. This is best modeled by statistical estimation theory, such as Bayesian.

Additional work in robotic modeling is found in Brooks (1991); Chown, Kaplan, and Kortenkamp (1995); Gopal, Klatzky, and Smith (1989); McDermott and Davis (1984); Yeap (1988); and Yoshino (1991). All of these models share certain concerns or ideas. First, they all posit multiple representations of space which vary in the degree to which they are dependent or independent of each other; as in Kuipers' SSH, some models suggest that different computational approaches or ontologies are most appropriate for different types of representations. All models include bottom-up processing from sensorimotor information, though the models vary in the degree to which they explicitly model perception-action processes derived from sensorimotor information rather than taking them as given. All posit the importance of landmarks that are noticed, remembered, and used to help organize spatial knowledge. In some way, all models concern themselves with the derivation of three-dimensional maps from two-dimensional views of the world. Further, they consider the derivation of allocentric (externally-centered) world models from egocentric (self- or viewpoint-centered) apprehension of the space; related to this is the construction of both local and global maps of the space. The different approaches vary in the degree of metric knowledge of distances and directions they posit in addition to topological knowledge; the metric knowledge is frequently modeled as being qualitative or fuzzy. The models all recognize the problem of integrating spatial information encoded in multiple frames of reference, and they generally employ some type of hierarchical representation structure such as graph trees to encode hierarchical spatial and thematic relations in the world.

3.4 FUNDAMENTAL RESEARCH QUESTIONS

Research on the cognition of geographic information addresses a host of fundamental issues in geographic information science. How do humans learn geographic information, and how does this learning vary as a function of the medium through which it occurs (direct experience, maps, descriptions, virtual systems, *etc*.)? What are the most natural and effective ways of designing interfaces for GIS? How do people develop concepts and reason about geographical space, and how does this vary as a function of training and experience? Given the ways people understand geographic concepts, do some models for representing information in digital form support or hinder the effective use of that information? How do people use and understand language about space, and about objects and events in space? How can complex geographical information be depicted to promote comprehension and effective decision-making, whether through maps, models, graphs, or animations? What are the contents of people's beliefs and value systems about places and features in built and natural environments? How and why do individuals differ in their cognition of geographic information, perhaps because of their age, culture, sex, or specific backgrounds? Can geographic information technologies aid in the study of human cognition? How does exposure to new geographic information technologies alter human ways of perceiving and thinking about the world? Several specific research questions can be identified as being of high priority at this time:

- Are there limitations of current data models that result from their inconsistencies with human cognitive models of space, place, and environment? What benefits could be derived from reducing these inconsistencies? Are there alternative data models that would be more understandable to novices or experts? How well can people understand common GIS operations such as buffer and overlay? Research on categorization indicates that humans understand what is essentially a continuous physical world in terms of discrete objects and places. How can the nature of human categories be incorporated into GIS? How do limitations of human categorization impact our ability to reason with geographic information? Self-report inventories and memory tests will help answer these questions, including sorting and category identification tasks.

- How can vehicle navigation system interfaces for wayfinding be designed and implemented in order to improve their effectiveness and efficiency for tasks such as route choice and the production of navigation information? Examination of errors and response times during the use of alternative systems will provide information on the strengths and weaknesses of particular designs.

- How can natural language be incorporated into GIS? How should it be? Issues to investigate include the interpretation of natural language queries, automated input of natural language data, and automated output of natural language instructions. Methods from linguistic and psycholinguistic studies can be focused on issues of geographic and spatial language.

- Spatial metaphors are frequently used to express nonspatial information ("spatialization"). For example, there is much interest in representing the semantic space of documents as a place or landscape. How can such metaphors best be used to represent and manipulate information? Both the speed and correctness of interpretations of spatializations can be tested, as well as the nature of the information browsing and searches they engender.

- How can GIS be used to represent and communicate important information in novel ways? Examples include information about error and uncertainty, scale and scale changes, and temporal information and process (as in animation). Performance measures can be collected on geographic tasks that require subjects to interpret the meanings of particular depictions of error, scale relationships, or temporal change.
- What are the possible applications of desktop, augmented, and immersive virtual-environment (VE) technologies to the exploration of information with GIS? What is the relationship of a VE format to traditional cartographic representations? Understanding the impact of such new media requires both systematic comparison to existing media and strategies for understanding novel experiential situations. Again, knowledge tests can be administered after exposure to VE representations, and compared to exposure to traditional map or verbal representations.
- How can geographic information technology be used to improve education in geography, and other earth and space-related disciplines? Conversely, how does research on child and adult learning and development inform us about the nature of human cognitive models, which in turn may have implications for the design of information technologies? What are ways of educating adults and children so that they have a better understanding of geographic information concepts and better access to its technologies? A variety of education research methodologies would contribute to answering these questions.

3.5 A CASE STUDY EXAMPLE: COGNITIVE ASPECTS OF VEHICLE NAVIGATION SYSTEMS

An example of the relevance of cognitive research to geographic information science involves the design of In-Vehicle Navigation Systems (IVNS), part of the broader topic of Intelligent Transportation Systems (ITS). Recently, systems have been developed to present navigational information to automobile drivers via digital displays. As of the writing of this chapter, these systems have moved out of the “experimental” phase and may be ordered as options in some new cars. Global Positioning System (GPS) technology, inertial navigation technologies, and digital GIS (including digital cartography) are being applied to the age-old problem of finding one’s way. But how should all of this information be supplied to the navigator, whether walking, driving, or piloting an airplane (Mark, Gould, & McGranaghan, 1987)? There is a real need to select information that is useful and relevant, and avoid presenting excess information that causes cognitive overload to the navigator. What is the best way to depict navigational information? All of these considerations must also take account of individual differences among navigators. Not everyone has the same abilities, preferences, or navigational styles. Cognitive research will improve our ability to properly tailor systems to individual users.

For example, Whitaker and CuQlock-Knopp (1995) examined these questions in the context of off-road navigation. They used naturalistic observation, interviews, and lab studies to attempt to identify the skills involved in off-road navigation, the features that are attended to, and the reasoning strategies used. They are attempting to apply this knowledge to the design of a useful electronic navigational aid (a prototype was called NAVAID).

Research has shown that the effectiveness of IVNS placed in automobiles depends on the modality and format in which information is depicted to the driver. Streeter, Vitello, and Wonsiewicz (1985) performed a study in which automobile drivers attempted to follow routes in an unfamiliar environment using either customized route maps, vocal directions (on a tape recorder), or both. The tape recorded verbal instructions presented about one instruction per turn, and did not include any information that was not shown on the route maps. On average, drivers using the verbal instructions drove for shorter distances, took less time, and made fewer errors than drivers receiving only route map depictions. Further research is needed to determine which types of features are most useful to be included in computer-generated verbal instructions and how these features should be described. Should the verbal instructions focus exclusively on landmarks and turn instructions? Or should information about distances be included? Is it beneficial to provide information about error correction or overshoots? Which features should be selected as landmarks (Allen, 1997)?

Providing map information to the driver in the visual modality is clearly a poor idea, if the driver attempts to read the map while steering the car. Maps are useful in certain circumstances, however, and preferred by some drivers. Research will help determine the best way to design these maps to optimize communication of geographic information to the automobile traveler. One important characteristic of in-vehicle maps is their orientation relative to the driver's direction of travel. As described above, most map users find it easiest to use maps during navigation when the map is oriented with its top being the forward direction of travel. Aretz and Wickens (1992) examined this preference, and the need to mentally rotate map displays that are not oriented in this manner. In addition to this rotation in the vertical plane, drivers mentally rotate map displays horizontally to bring them into correspondence with the forward view. These mental rotations have a cost, and produce slower and less accurate interpretations of electronic map displays. However, Aretz (1991) documents that a fixed map orientation, such as "north-up", while it requires mental rotation, better supports the development over time of a cognitive map of the surrounds. Software and hardware must be implemented to support a driver's choice of either a fixed map orientation or real-time realignment of digital maps during travel.

Aside from the questions of what information to supply to drivers, and how best to display it, there are other important questions about vehicle navigation systems that may be addressed by cognitive research in GIS. “Do we need them, in what situations do we need them, and what will be their ultimate effects on the experience of the driver?” Having navigational information available in rental cars to new visitors is likely to be of great value. Survey or observational research might find, however, that residents of a place very rarely need such a system. A driver familiar with the area may not use a vehicle navigation system enough to make such a system worth its cost. Assuming such systems become common, we might further conjecture about the effects they will have on the driver’s experience and phenomenology of the world (Petchenik, 1990). Will the wide-spread use of such technologies impair our traditional abilities to navigate and learn space unaided by the technologies (Jackson, 1997)?

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