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# Cognitive Research in GIScience: Recent Achievements and Future Prospects

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## Abstract

In this article, recent achievements of cognitive research in geographic information science (GIScience) are reviewed and prospects for future directions discussed. Cognitive research in GIScience concerns human knowledge and knowing involving geographic information and geographic information systems (GIS). It includes both internal mental and external symbolic structures and processes, and is practically motivated by the desire to improve the usability, efficiency, equity, and profitability of geographic information and GIS. Taking 1992 as the start of modern GIScience, recent cognitive research falls into six areas: human factors of GIS, geovisualization, navigation systems, cognitive geo-ontologies, geographic and environmental spatial thinking and memory, and cognitive aspects of geographic education. Future prospects for cognitive GIScience research include recommendations for methods, including eye-movement recordings and fMRI; theoretical approaches, including situated cognition, evolutionary cognition, and cognitive neuroscience; and specific problems, including how users incorporate uncertainty metadata in reasoning and decision making, the role of GIS in teaching K-12 students to think spatially, and the potential detrimental effects of over-reliance on digital navigation systems.

## *Introduction*

Cognition concerns knowledge and knowing in intelligent entities, especially human beings but also nonhuman animals and synthetic computational entities such as robots (Montello 2008; Wilson and Keil 1999). Cognition includes internal mental structures and processes involved in perception, attention, thinking and reasoning, learning, memory, and linguistic and nonlinguistic communication. It also includes external symbolic structures and processes, such as maps or the written procedures for carrying out a formal spatial analysis, which assist internal cognition. Increasingly, researchers are studying the role of emotion in cognition, as well.

Cognitive research incorporates several disciplines, including psychology, philosophy, linguistics, neuroscience, computer and information science, and others. In their review of earlier cognitive research relevant to geographic information science (GIScience), Montello and Freundschuh (2005) found that a variety of theoretical and methodological perspectives had been brought to bear on the study of cognition. A list of such perspectives includes: psychophysics, constructivism, the ecological approach, the information-processing approach (including traditional rule-based artificial intelligence), connectionism and neural networks, linguistic/category theory, socially and culturally situated cognition, evolutionary cognition, and cognitive neuroscience. They also noted that different researchers have focused on different parts of the broad subject matter of cognition, ranging from relatively low-level and implicit (non-conscious) processes to relatively high-level and explicit processes. Similarly, cognitive researchers' domains of interest vary in whether they depend mostly on sensing, on moving, on memory of various types, on communication with others, and so on. Thus, different theoretical approaches are partially complementary rather than strictly contradictory.

Montello and Freundschuh (2005) reviewed the historical roots of cognitive research in geography, cartography, and GIScience. Since at least the 1960s, cognitive research has included geography and cartography, and since the inception of GIScience in the late 1980s and early 1990s, it has included that as well. In fact, the study of cognition has been a fundamental research domain for GIScience from its beginning, and this status continues to this day. For example, it was one of the 13 topics in the first-published list of research priorities by the University Consortium for Geographic Information Science (McMaster and Usery 2005). Geographic information is meant to help people understand and make decisions about the Earth's surface, and the spatio-temporal and thematic attributes of the features and events found there, whether natural or human. Understanding and decision making are cognitive acts. Likewise, cognition is often about space, place, or environment, so that cognitive acts are often geographic.

From a practical perspective, the study of cognition in GIScience is motivated by the desire to improve the usability, efficiency, equity, and profitability of a wide variety of geographic information and GIS. By helping to tailor information systems to different individuals and cultures, cognitive research holds the promise of increasing information access and the equitable dissemination of technologies. Such research may help inexperienced users gain access to geographic information technologies, and help experienced users gain power and efficiency in their use of technologies.

## *Recent Achievements of Cognitive GIScience Research*

This section critically reviews the recent scientific literature on cognitive research in GIScience. To constrain the review, it focuses on research specifically involving geographic information and geographic information systems (GIS). Geographers and cartographers wrote most of this literature, although psychologists, computer scientists, linguists, and philosophers contributed a sizeable portion. There is also a much wider body of literature concerning general spatial or geographic cognition. Although this research is probably relevant to GIS, it is beyond the scope of this study to cover it all, and much of this wider body of literature has not explicitly been applied to GIS.

I take the year 1992 as a starting point for the modern era of GIScience research, including cognitive research, and thus as the starting point for this review. This is not completely arbitrary. As mentioned above, there certainly was research on the cognition of space, place, maps, and environment before 1992, but it was only since the late 1980s and early 1990s that researchers specifically identified the need for cognitive research to address questions surrounding digital geographic information and GIS (as opposed to, e.g. cartography or spatiality in general). The year 1992 was when Goodchild (1992) first coined the term 'geographic information science' to refer to the multidisciplinary research field investigating scientific questions, including cognitive questions, about geographic information and GIS. Nothing before that went by the name geographic information science. Finally, research on cognitive geography and cartography before 1992 has already been reviewed several times, by Gärling and Evans (1991), Gärling and Golledge (1993), Golledge and Stimson (1997), Kitchin and Freundschuh (2000), Mark and Frank (1991), McNamara (1992), Montello and Freundschuh (2005), Petchenik (1983), Portugali (1996), and others.

Finally, given that the present article focuses on *scientific* research, it does not review the literature from humanities traditions, including humanistic, phenomenological, and approaches such as postmodernism. Examples of humanities literature concerning geography and human mentality include work by Tuan (1977), Buttimer and Seamon (1980), Guelke (1989), Cresswell (2004), and Wood (2004). Although the humanities tradition offers rich and valuable thinking on space, place, mind, and behavior, it is not easily commensurate with scientific writing on these topics, as the two traditions differ substantially in their intellectual goals, fundamental conceptualizations (ontology), and methodologies (epistemologies) (see Montello and Sutton 2006, for additional discussion of these contrasts in geographic research).

Below, specific areas of recent cognitive research in GIScience are reviewed and critically evaluated. In addition to these specific areas, there have been several general overviews of this research area since 1992 (Egenhofer and Golledge 1998; Kitchin and Blades 2002; Mark et al. 1999). Two publications are arguably the most important in this respect, as they provide a general overview of cognitive research within the broad context of the whole field of GIScience. These are *Representations of space and time* by Peuquet (2002) and *Multidimensional geographic information science* by Raper (2000). These authors' efforts are quite ambitious, and their books stimulate us to consider whether GIScience is coherent as a discipline, or at least a problem area. GIScience involves knowing about geography, cartography, surveying, mathematics, computer science, psychology, philosophy, linguistics, economics, sociology, and more. It is asking a lot to expect any individual to achieve expertise in such a diverse array of fields; integrating all of it is even more challenging. But it is just such an integration of many diverse areas of intellectual content and method that is the central challenge of GIScience. Arguably, without such a coherent integration, there is little warrant for referring to 'GIScience' as a single entity.

The review of recent cognitive research is organized into the following six specific areas: (i) human factors of GIS, (ii) geovisualization, (iii) navigation systems, (iv) cognitive geo-ontologies, (v) geographic and environmental spatial thinking and memory, and (vi) cognitive aspects of geographic education. I organize the research into these topical areas because it summarizes well the research activity in cognitive GIScience since 1992. The areas are all related, of course, insofar as they all involve geographic information, and the human cognitive acts of understanding and decision making. All of them concern how humans interact with geographic information and GIS, and how we can improve this interaction by making it more functional, more efficient, more enjoyable, and more equitable.

## HUMAN FACTORS OF GIS

The first area of research focuses specifically on the interaction between humans and information systems. Human factors, or ergonomics, is an applied area of research that aims to improve the human usability of designed systems, devices, and environments. Usability expresses ease of learning and using, effectiveness, safety, and pleasantness of use. All aspects of usability are potentially relevant, including sensory-motor, cognitive, affective, and social aspects. In the context of GIScience, human factors research has addressed questions about the congruency between computer representations (data models, data structures) and human cognitive representations of space, place, and environment (cognitive or mental maps, mental models); the design of information displays, including visual and nonvisual displays (discussed in the next section on geovisualization), and augmented and virtual reality; the human factors of navigation and other information systems (discussed below); and more (Davies and Medyckyj-Scott 1996; Medyckyj-Scott and Hearnshaw 1993; Nyerges et al. 1995).

An important subset of human factors research in GIScience has looked at the nature of reasoning and decision making with geographic information. This research has examined situations where people use GIS to make decisions such as facility siting, route choice, and climate forecasting (Ishikawa et al. 2005). Some of these studies have considered the social nature of cognition, examining how decision making with geographic information works when it is socially distributed or collaborative. For example, Jankowski and Nyerges (2001) conducted experiments with small groups of research participants who were asked to assume the roles of various stakeholders in the design of habitat restoration sites. Multiple-criteria decision models were used along with GIS to solve these problems. Among other findings, these researchers found that participants used maps a great deal to visualize results of site evaluation but not as much to actually pick the sites.

Much of this human-factors research fits into the domain of human–computer interaction (HCI). A common HCI approach to assessing the usability of GIS is to observe and interview GIS users about how well their systems meet their needs (e.g. Yuan and Albrecht 1995). Although a great deal of insight can be gained this way, researchers in this area do not always recognize the limitations of explicit reports as data. This is especially true for questions about how and why people do things. People do not have conscious (i.e. explicit) access to all of their cognitive structures and processes. Nor is all of a person's explicit cognition in a linguistic form that can be well expressed with verbal measures, such as surveys (Montello and Sutton 2006). Multiple methods, including nonverbal measures, need to be used.

### GEOVISUALIZATION

As stated above, a specific human-factors concern within GIScience has been with the design of information displays. Although a subset of human factors, this research area deserves separate recognition because it continues the long tradition of studying cognitive aspects of cartographic communication (Lloyd 1993; Montello 2002). Also, I believe it is the clearest case of cognitive research within GIScience that can provide the practical benefits of improving the usability and accessibility of GIS.

Maps comprise often-complex systems of signs and symbols whose interpretation depends profoundly on a person's prior knowledge and learning experience. There are thus many interesting and subtle questions for researchers interested in the cognition of geographic information displays (see the comprehensive review by MacEachren 1995). The recent research in this area differs in at least two significant ways from research during the 1960s and 1970s heyday of cognitive cartography. First, the notion from the communication paradigm that the functioning of maps is just a matter of the mapmaker's message being successfully sent to the map user has been significantly modified. It has been replaced by the notion that both mapmakers and users have their own mental models of the world; map communication is almost never a process of one person's model simply being transferred to another. Instead, aspects of the mapmaker's model not only influence aspects of the map user's model but also stimulate ideas in the user's mind that were neither in the mapmaker's mind nor 'in' the display itself. Second, the use of static, two-dimensional (2-D), passively displayed visual maps as research material has been expanded to include displays that are interactive, dynamic, multisensory (the term 'visualization' notwithstanding), spatially 3-D, and more (Griffin et al. 2006; Koua et al. 2006;

Lauriault and Lindgaard 2006; Rice et al. 2005). A significant area of cognitive research on geovisualizations, for instance, has addressed the question of what are effective ways to depict data quality or uncertainty (Aerts et al. 2003; Evans 1997; Yao and Jiang 2005). Unfortunately, the essential questions of how users *should* and *do* make use of uncertainty metadata to make decisions is virtually completely overlooked in the geovisualization community. This point is discussed further below.

Slocum et al. (2001) reviewed six cognitive research areas involving geovisualization: (a) geospatial virtual environments; (b) dynamic representations; (c) metaphors, schemata, and interface design; (d) individual and group differences; (e) collaborative geovisualization; and (f) evaluating the effectiveness of geovisualization research methods. For example, research by Fabrikant et al. on the use of spatial displays to metaphorically represent the semantic content of large databases provides an important body of research in area (c), on metaphors, schemata, and interface design. Such displays are known as 'information spatializations.' Typically, a document with semantic content, such as a newspaper article, is represented as a point in semantic space, the dimensions of which capture some aspect of meaning in the document. The location of a point relative to other points metaphorically represents the semantic similarity of the documents depicted by the points. Generally, more similar documents are located more closely to each other, a design principle called the 'distance–similarity metaphor' (Montello et al. 2003a). A variety of other visual elements are also used to suggest semantic relationships among documents, including the pattern and width of network links, region membership and proximity, and color hue and value (Fabrikant et al. 2004, 2006). In a series of empirical studies with human participants, these researchers have found support for the distance–similarity metaphor in point displays unless the points form emergent lines or clusters that increase rated similarities. They have also found that similarity judgments in network displays follow network links and not direct spatial relationships (Figure 1), but link width and color patterns can greatly modify apparent similarity among documents. Finally, region boundaries around points greatly modify distance–similarity relationships, especially when the regions are colored in particular ways.

A strength of the research program by Fabrikant et al. is its use of controlled stimuli evaluated in a controlled task situation. This is also its weakness. Research participants have been undergraduate college students who had no real motivation to understand the content of the spatialized displays and were given almost no problem context for their interpretations (for example, the points were described as documents without stating what topics they involved). Also, the designers of visualizations base their construction of information spatializations on their insight that humans can naturally interpret huge amounts of information in realistic landscapes in a highly efficient manner. This is considered to arise both from the biological evolution of the human species, and personal and cultural learning. But Fabrikant et al. studied simple and rather artificial stimuli, such as fields of points, that did not resemble actual natural or anthropogenic environments on the Earth.

### NAVIGATION SYSTEMS

The third area of recent cognitive GIScience research has investigated navigation systems, including those involving maps and verbal route directions. This extends the human factors of information displays discussed above specifically to the important geographic and environmental domain of human navigation, which is a coordinated and goal-directed travel. Virtually all of this research has focused on the wayfinding component of navigation, which includes planning trips, choosing routes, and orienting to distant places and landmarks (Golledge 1999; Montello 2005). It is usually important that travelers are spatially oriented while

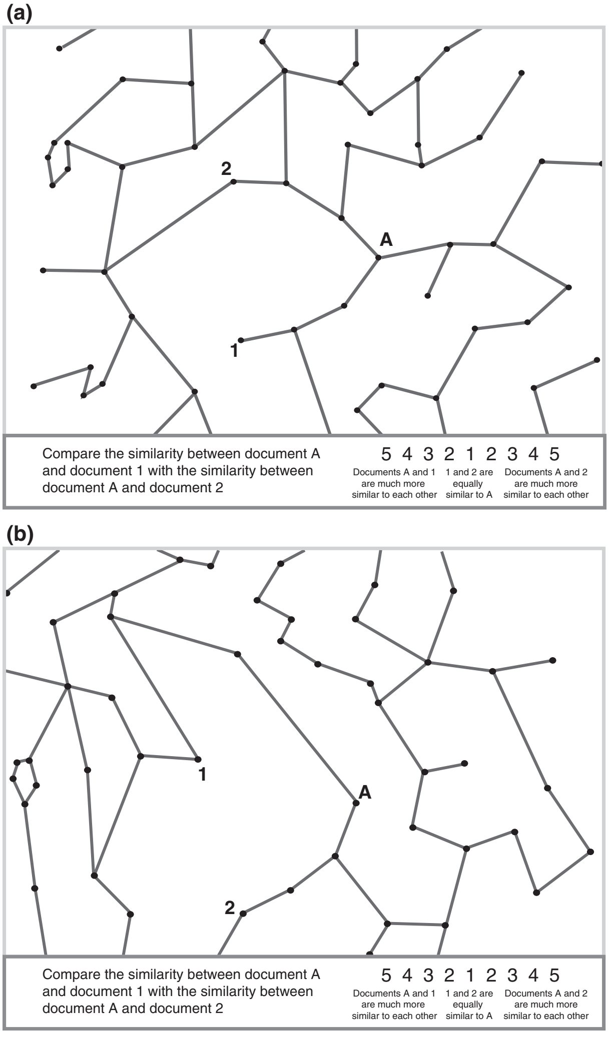


Fig. 1. The effect of distance on similarity ratings in a network spatialization: (a) direct, node, and network distance equal, document pairs A:1 and A:2 not rated significantly different in similarity from each other, and (b) direct and node distance equal, network distance unequal, document pair A:2 rated significantly more similar than A:1 (adapted from Fabrikant et al. 2004).

moving through the environment – they must maintain some awareness of their location relative to their destination or other places. However, successful navigation often requires only approximate orientation, such as knowing whether one is traveling in the correct direction or is on the correct train. Cognitive GIScience researchers have addressed questions about the best modality for navigation information – cartographic, verbal, or otherwise – and the specific content and form of this information.

This points to one of the most significant challenges to this area of research: how to provide travelers with just the information they want and need, and not more. The challenge has not yet been met. For instance, recent research has investigated the schematic abstraction of map displays, such as subway maps, from a cognitive perspective

(Berendt et al. 1998). Clearly, most people do not need or want precise and detailed spatial information when they are traveling along road or rail networks. But some people may appreciate more details and metric accuracy, and it appears that highly schematic maps may be misinterpreted in some contexts. As another example, Klippel (2003) proposed an interesting abstraction for navigation maps that uses a small set of symbols, called 'choremes', to capture basic human concepts of path structure and locomotion. In many situations and for many people, verbal route directions provide the best way to communicate navigation information to people (Allen 1997).

Some researchers (Denis et al. 2007; Raubal and Winter 2002) have maintained that people significantly benefit from the inclusion of named landmarks in route directions, and they have conducted research to determine which landmarks would be most useful for this purpose. A major goal of such research is to automate the selection of landmarks for navigation systems. Progress continues to be made, but thus far, even experimental navigation systems fall short by including significantly too much or too little detail for different travelers.

### COGNITIVE GEO-ONTOLOGIES

The fourth area of cognitive GIScience research, which, like the first three areas, reflects the GIScientists' interest in human interaction with information systems, concerns cognitive ontologies. Unlike traditional philosophical ontology, a component of metaphysics that asks about the ultimate nature of reality, cognitive ontology recognizes that the nature of human understanding about features and events in the world results from the nature of human perception and conception as critically as it depends on the nature of reality itself. In other words, the study of cognitive ontologies is essentially the study of conceptual structure and change. Referring to ontologies in the plural recognizes that conceptualizations may vary among cultures and even individuals, as well as among different computer representations of reality ('formal' ontologies – see Guarino 1998). Ironically, nearly all of the modern research on geo-ontologies is as much about epistemology as it is ontology.

Interest in cognitive ontologies in the GIScience community has been stimulated by a recognition that digital representations of geographic information, such as in databases, are necessarily particular models of the reality represented, not the reality itself. Thus, a variety of GIS issues, such as interoperability between systems, depend on the relative semantic commensurability of different models of geographic phenomena in different systems (Agarwal 2005; Bittner and Edwards 2001; Kuhn et al. 2007; Timpf 2002).

In one of the most influential and cited articles in cognitive GIScience, Egenhofer and Mark (1995) characterized the geographic conceptualizations of lay people as 'naive' or 'commonsense' geography. Vosniadou and Brewer (1992) provided one of the finest examples of research on naive geography in their study of the development of commonsense understanding of the Earth by children. Samarapungavan et al. (1996) followed this up by studying the commonsense cosmology of the sun and moon. Ontology researchers are also interested in expert conceptualizations of geographic phenomena, such as geologic features (Brodaric et al. 2004; Hoffman and Pike 1995).

Research on geo-ontologies such as that cited above struggles with the persistent and thorny intellectual issue of the relationship of language and thought. Concepts can be thought of as rules that define category systems. Much of the research on cognitive geo-ontologies has, in fact, been stimulated by cognitive and linguistic category theory (Gray 1997; Mark 1993; Usery 1993). In their extensive research program, Mark and colleagues have investigated the ontology of landscape features, such as mountains and valleys, by members of a various cultural groups (Mark et al. 2001, 2007; Smith and Mark 2003). These researchers typically use a methodology that asks respondents to list verbally examples of types of geographic features or supply verbal labels for pictures of portions of the Earth's surface. Their recent work has included hunter–gather and simple agricultural cultures, including the Navajo people of the southwestern USA and the Yindjibarndi people of western Australia. They report some significant differences in the way these groups conceptualize landscape features as compared to English speakers. However, their research stimulates one to consider whether concepts and words have one-to-one correspondence. If they do not, as some cognitive scientists believe, it is not sufficient to study ontologies by relying exclusively on explicit verbal reports. Is there geographic meaning that is not captured well by words? Does expressing geographic meaning in verbal form act to modify it in any way from its nonverbal form?

A central concern for researchers studying cognitive ontologies has been the issue of spatial and conceptual indeterminacy or vagueness (Burrough and Frank 1996). Unlike classical categories, which identify category membership by a finite set of necessary and sufficient properties, the categories people actually use to capture the meaning of reality tend to be ill-defined, without precise referents or sharp boundaries. Membership in such natural categories is rarely either-or but usually probabilistic – a matter of degree. There has been a great deal of interest in formally describing vague categories so they can be digitally implemented in GIS. For example, Robinson (2000) and Wang and Hall (1996) have applied fuzzy logic to the modeling of imprecise spatial language terms such as 'near' and 'large'. Montello et al. (2003b) explored empirical methods for determining people's vague boundaries of cognitive regions. This is potentially one of the most fruitful areas of research in cognitive GIScience, insofar as it differentiates human thinking and communication so strongly from the way traditional digital systems represent meaning, but it continues to fall short of handling the context-dependent nature of vagueness in human thought. Whether two places are 'near' or 'far' depends on the scale context of a situation and also on the purpose or function of a query.

### GEOGRAPHIC AND ENVIRONMENTAL SPATIAL THINKING AND MEMORY

The fifth area of recent cognitive research in GIScience complements the areas reviewed above in that it looks more at cognition of the real-world referents of geographic information than at cognition of the digital information systems and databases themselves. This area concerns spatial thinking and memory, specifically about environmental and geographic spaces. A key issue here has been the degree to which spatial knowledge is continuous or discrete. This is key because it echoes a discussion in GIScience about field and object ontologies for geographic space, which in turn relates to the raster–vector debate in GIS. Clearly, human conceptualizations of space incorporate various discrete or nearly discrete entities, such as landmarks. Similarly, people categorize the Earth's surface into discrete regions, which organize memory, influence reasoning, and provide referents for verbal labels. Research by Friedman and colleagues (Friedman and Brown 2000; Friedman et al. 2005) has demonstrated the influence of regional organization at the continental level. Students distort estimates of the latitudes of cities within a region (such as northern Europe) toward values similar to other cities within the region but away from cities in neighboring regions (such as southern Europe). This within-region compression and between-region expansion of estimated latitudes is evident in Figure 2, which plots actual and estimated latitudes for several world cities.

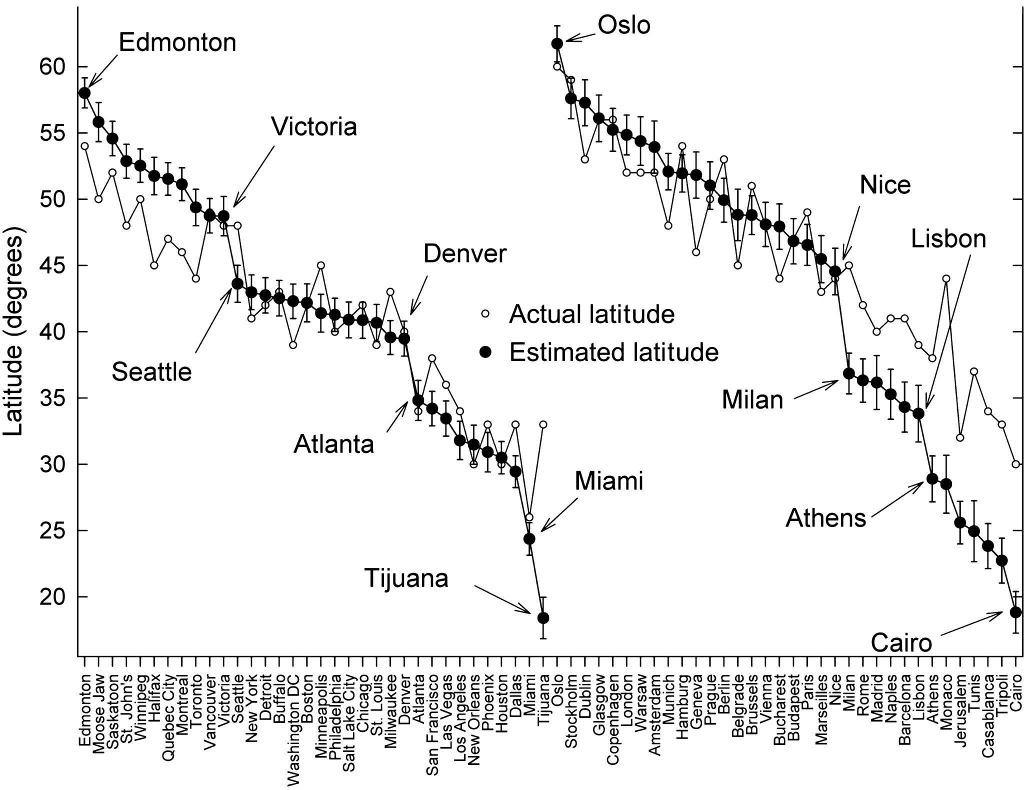


Fig. 2. Mean estimated latitudes of world cities by 60 college students; actual latitudes, the symbols without error bars, are plotted for comparison (from Friedman and Brown 2000).

Examining Figure 2 shows that cities were not estimated in this study only by their membership in a specific cognitive region. For example, these Canadian students estimated latitudes of the range of Canadian cities in fairly close correspondence to their actual latitude range (albeit overestimating them overall). Edmonton was the most northerly Canadian city rated in the study, and the students estimated it as most northerly. Thus, human spatial knowledge is not just qualitative; it is also somewhat continuous and quantitative. An influential model by Newcombe and Huttenlocher (2000) attempts to describe the way discrete and continuous spatial knowledge combine in various spatial knowledge tasks. Their 'category-adjustment model' proposes that location is mentally coded in multiple ways, incorporating both coarse categorical knowledge and relatively fine-grained metric knowledge. According to the model, the less that people can recall fine-grained knowledge, the more they rely on categorical membership to judge location. The behavioral signature of categorical knowledge is distortion of recalled location toward prototype locations (such as the center of a region). Thus far, their model has proved very fruitful in accounting for spatial memory in an increasing array of stimuli and recall situations.

The partially discrete and nonquantitative nature of human spatial thinking has been computationally modeled through the development of *qualitative* models of cognition. These models represent spatial knowledge using nonmetric or imprecise metric geometries, and simple reasoning procedures (Freksa 1992; Ligozat 1993; Zimmermann 1993).

For example, Frank (1996) presented a widely cited qualitative model for reasoning with cardinal directions. His model proposed that humans make spatial inferences with a small number of directional equivalence classes, modeled as either four or eight cones or half-planes. The model's inference rules allow for the treatment of directions close to each other as being of the same class, thus providing a mathematical formalism for indeterminacy in approximate qualitative reasoning.

From a basic-science perspective, the research on geographic and environmental spatial thinking and memory is among the most accomplished of all cognitive GIScience research. But its application to information systems remains unclear. After all, why would one want to implement the biases and fallibilities of human spatial thinking in information systems when one of the major reasons for their use is to overcome these limitations?

### COGNITIVE ASPECTS OF GEOGRAPHIC EDUCATION

The sixth and final area of recent cognitive GIScience has focused on cognitive aspects of geographic education. This is education about the human and natural environments of the Earth, in reality and as represented in information systems, echoing the foci of the first five research areas. As part of this, a longstanding research interest in education with and about maps has continued. The 1990s debate about the nature and development of children's understanding of maps reviewed by Montello and Freundschuh (2005) has been largely resolved. One side (Blaut 1997) had argued that young children (ages 3–5) understand aerial photographs and simple map-like representations because they have a 'natural' ability at mapping. The other side (Liben and Downs 1997) argued that children demonstrate difficulties and confusions when attempting to understand maps because the development of mapping skills such as symbolic correspondence and the transformation of spatial perspectives are difficult and require somewhat extended development over childhood. In fact, although some abilities to make and understand map-like symbols are present earlier than a strict Piagetian interpretation would suggest, and mapping probably should be introduced earlier in school than has widely been held, evidence supports that there is a suite of different skills involved in mapping that take time and experience to develop (see Liben 1999). Various literature documents that even adults find some mapping tasks difficult; interpreting contour lines is one example.

In fact, the emergence of map-like thinking may not be nearly as 'natural' as researchers like Blaut have argued. Uttal (2000) proposed that adults in modern and postmodern cultures think as they do about space and environment only because of their exposure to cartographic maps. He argued that a fully integrated, vertical 'bird's-eye' perspective of spatial layout is not a human universal. Uttal makes a strong and intriguing case for his provocative proposal, although I continue to believe that child developmental, cross-cultural, and historical evidence is most consistent with a theoretical framework in which a survey understanding of the Earth's surface is a human universal, although it does require aging and experience to fully mature.

The US National Research Council recently published an important book written by the Committee on Support for Thinking Spatially (2006) called *Learning to think spatially*. The committee maintained that spatial thinking is a fundamental mode of human thought, but that it receives short shrift in the education curriculum. The committee thus called for educational standards in spatial thinking. They also argued that incorporating GIS and other spatial technologies into the K-12 curriculum would be very valuable as a way to teach spatial thinking and reasoning. At the same time, the committee recognized some of the limitations of GIS as a support system for spatial thinking. They did not make a naive, unconditional call for GIS and other technologies in the classroom, but they did claim that technology could assist and extend cognition. This book is important and has an overdue message for communities outside of GIScience, but I wonder about their claim that geographic information technologies will aid and enhance, rather than substitute and weaken, the spatial thinking abilities endemic to the human animal. This issue is discussed further below.

*Future Prospects: Where Should Cognitive GIScience be Headed?*

Given this review of recent research activities in cognitive GIScience, we can consider recommendations for its future. Where should research in cognitive GIScience be headed? Clearly, GIScientists should continue to pursue understanding some of the important issues they are already working on, including the best ways to visualize complex geographic information, such as uncertainty and other metadata; the nature of individual and group differences in geographic information cognition; effective training and education in GIS, geography, and other earth and environmental sciences; cognitive ontologies and their formal representation; and applications of virtual and augmented reality (the time is ripe, if not overripe, for studies on Google Earth).

One clear avenue for GIScientists to explore is the application of additional methodologies and theoretical perspectives to problems of geographic information and GIS. As a case in point, eye-movement recordings have a history in cartographic research (see Montello 2002), but technical difficulties and an inadequate development of theory resulted in cessation of such work before much was achieved scientifically. However, the method is widely and fruitfully applied to cognitive research outside of GIScience, and it holds promise for new insights within GIScience as well (e.g. Fabrikant et al. 2008).

Cognitive GIScientists clearly have not explored all the theoretical perspectives reviewed above that are available to those who study cognition. In particular, although GIScientists and their intellectual ancestors have rather thoroughly explored perspectives such as psychophysics, constructivism, the ecological approach, and linguistic/category theory, they have not paid as much attention to situated cognition, evolutionary cognition, and cognitive neuroscience. Cognitive neuroscience, in particular, has recently become one of the most active areas of research in all of science. This perspective attempts to explain cognition by relating it to the structures and processes of brains. [In contrast, the neural networks that some GIScientists have explored (Lloyd 1997) are only computational models loosely inspired by the idea of many simple units interconnected in complex ways, like neurons in the brain.] A variety of techniques are available to cognitive neuroscientists, but its recent surge in popularity primarily results from the increasing use of functional Magnetic Resonance Imaging (fMRI) to scan the healthy brain activity of alert human research participants at relatively high spatio-temporal resolution. Although researchers outside of GIScience have been using fMRI to examine brain activities associated with spatial and nonspatial thinking, cognitive GIScientists have just begun to explore its promise (Lawrence et al. 2005).

There are a few specific research issues that deserve more attention. Above, we reviewed research on the depiction of uncertainty and quality metadata in geovisualizations. As noted, however, almost no work has addressed the questions of how users incorporate uncertainty metadata in reasoning and decision making. In fact, there is a stunning paucity of evidence in GIScience as to whether such metadata influences decision making at all. Work by Hunter and colleagues (Agumya and Hunter 2002; Hope and Hunter 2007) provides a rare exception, but in my view, the issue deserves much more research attention than it has received. There is an extensive literature in psychology and economics on decision making under conditions of risk or uncertainty, a little of which was applied some time ago to spatial decision making by behavioral geographers (Golledge and Rushton 1976). But very little of this has been applied by GIScientists in the context of decision making with uncertainty metadata. MacEachren et al. (2005) provide a concurring view and elaboration.

Another specific issue on which I would like to see more research is the claim by the NRC's Committee on Support for Thinking Spatially (reviewed above) that GIS is a good way to teach K-12 students to think spatially. GIS is not exclusively spatial (neither is geography more generally). It is thematic, temporal, and logical in nonspatial ways. It incorporates words, numbers, and other symbols whose interpretation is not particularly spatial (except at the implicit level of visual recognition). In fact, much of the spatial cognition that takes place when using a GIS really just involves perceiving patterns on a computer screen; it does not necessarily involve much spatial memory, inference, or reasoning. For instance, when a user wants to know if any felons live within some distance of a school, he/she does not necessarily think spatially but types or clicks 'buffer', and looks at the result.

Finally, another important issue for cognitive GIScientists to continue pursuing involves navigation systems. The widespread dissemination of these systems in technologies such as cell phones provides an incentive for a variety of research studies, such as how information can be effectively shown on small displays (e.g. Dillemuth 2005). But I believe we need more research on the potential detrimental effects of over-reliance on digital navigation systems. Members of the GIScience community (certainly not just the cognitive ones) often tout the benefits of technology, and the whole enterprise of GIScience can be seen as a celebration of the potential of digital technologies and an attempt to make them work better, and thus be more widely adopted. However, there are many historical examples of technologies replacing and thereby weakening human intellectual abilities. Technologies change how we think, often by reducing our ability to reason effectively without the technology (so-called technological 'infantilizing'). Modern humans cannot navigate without technological aids as some people once could. This may not be considered a problem as long as one's technology is available and in working order. But stories have begun to accumulate that anecdotally document how GPS and related technologies have left people disturbingly lost when the satellite reception goes down or the batteries run out. This is not an easy research problem, as it probably requires long-term longitudinal research that is difficult to carry out well. There are only a couple of examples of systematic research on this issue (Ishikawa et al. 2008; Parush et al. 2007).

## *Conclusion*

Cognition is one of the fundamental areas in GIScience, and in turn, GIScience is one of the cognitive sciences. Without doubt, there are interesting and important basic research questions concerning cognitive structures and processes involved in using geographic information and GIS that go well beyond mundane issues such as how to get a particular GIS package to perform some operation. Intellectually engaging and challenging issues include representing dynamic change, depicting multivariate data effectively, handling 3-D phenomena, incorporating useful metadata, enabling interoperability, communicating multiscale representations, representing and depicting vagueness, and making the growing body of geographic information accessible to lay people. And because cognitive research attempts to explain portions of reality with the use of systematic empirical methods, it constitutes a clear example of *scientific* research with geographic information.

Furthermore, the notion that understanding human cognition should help improve the use of geographic information and GIS makes sense and seems valid. But it must be noted that the applied payoff of cognitive GIScience research has been minimal to this point. There are only very few examples of modifications to the way geographic information is collected, stored, processed, or accessed that can be traced to cognitive research. There are a variety of reasons for this, ranging from economic and technological inertia to the difficulties of making products that can accommodate people with a variety of cognitive styles, abilities, and experiences. Doing good cognitive GIScience research is difficult. And we should not forget that people use GIS largely to overcome their own cognitive limitations of memory and thought, not to be forced to wallow in them, as noted above. Thus, it is surely one of cognitive GIScience's greatest challenges as an applied discipline to clarify its value in the design and use of geographic information technologies.

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*Short Biography*

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