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SOURCES OF SPATIAL KNOWLEDGE AND THEIR IMPLICATIONS FOR GIS: AN INTRODUCTION

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What and how people think about geographic space depends in important ways on how knowledge of the properties of that space, and of the objects and events within that space, has been acquired. The premise of this special issue of *Geographical Systems* is that understanding human perception and cognition of space is necessary in order to arrive at a complete understanding of human reasoning, decision-making, and behavior that involves knowledge of space. In particular, it is necessary to understand how spatial knowledge and its use differs as a function of the source from which that knowledge is acquired. Does this idea have implications for the design and use of geographical information systems? It is the contention of this issue that it does. The purpose here, therefore, is to justify these premises and investigate ways in which they might be realized.

The five papers included in this issue are based on talks given at a pair of special sessions held at the 1994 Annual Meeting of the Association of American Geographers in San Francisco, California. The theme of those sessions was "sources of spatial knowledge and resulting cognitive representations". Session participants were invited to give papers dealing with basic science questions about how spatial knowledge and reasoning might be influenced by the source from which knowledge is acquired. The varied backgrounds of the participants reflect the multidisciplinary (hopefully interdisciplinary) nature of this question—geographers, cartographers, and psychologists of various stripe, including cognitive, environmental, and developmental. It is fair to say that this represents only a few of the disciplines that can speak to the issues. A comprehensive list might also include linguists, computer scientists, anthropologists, philosophers, art historians, planners and architects, and communication specialists—perhaps others.

KEY WORDS: spatial cognition, spatial knowledge sources, cognitive representation, GIS

ACQUIRING SPATIAL KNOWLEDGE

The scientific study of spatial perception and cognition began in the 19th century, but of course was derived from the philosophical theories of earlier times. In the present century, psychological questions about space have 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, processes and structures used during navigation, as well as perceptual and cognitive issues in cartography, and very recently, geographic information systems (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. We believe that several interesting and important questions for GIS research and design are related to issues of human perception and cognition of space and spatial information. Nonetheless, the potential of this research area has only been hinted at thus far (see Egenhofer and Golledge, 1994; Mark *et al.*, 1989; Medyckyj-Scott and Hearnshaw, 1993).

Throughout the history of research on the psychology of space, a variety of metaphors have been offered as summary descriptions of human spatial knowledge of the environment. As is generally true with metaphors, they capture useful meaning and facilitate communication by casting the unknown in terms of the known. Unfortunately, they also invite us to understand the unknown in terms of characteristics of the known that do not apply (e.g., Downs, 1981; Johnson, 1987; Lakoff, 1987). The list of metaphors for environmental spatial knowledge is large (and growing). This can be appreciated by reference to the following lists of terms that have been or could be used as labels for knowledge of spatial relations in the environment.[1] Choose a spatial adjective from A and a cognitive noun from B:

A: Spatial Adjective	*B: Cognitive Noun*
spatial	knowledge
environmental	representation
place	model
geographical	schema (schemata)
layout	image
orienting	
topological	
metric	
geometric	
topographic	
world	
landscape	

Alternatively, choose a cognitive adjective from A and a spatial noun from B:

A: Cognitive Adjective	*B: Spatial Noun*
cognitive	map
mental	model
internal	configuration
perceptual (perceived)	space
conceptual	atlas
subjective	collage
psychological	projection
memorial	world
propositional	landscape
neural	layout
	environment
	network
	graph
	geometry

Of course, these 200 combinations are not exactly synonymous. Choosing one over another would explicitly or implicitly indicate a theoretical assumption (such as the level of geometric sophistication of knowledge) or at least a delimitation of the domain of interest (such as a focus on some scales rather than others). If these 200 aren't sufficient, other adjectives may be added to further differentiate. For example, the adjective "spatial" is often put at the front of a two-word phrase for extra emphasis (e.g., "spatial cognitive model"), or words like "route" or "survey" are added for greater specificity.

It is only natural that GIS would be offered as a metaphor for spatial knowledge, as in "cognitive GIS". Peterson (1995), for example, has suggested the metaphor of human geographic information system (HGIS) to encompass the cognitive input, processing, and display of information necessary to interact with the environment. Golledge (1992) also raises the similarities between compiling and using cognitive maps and compiling and using a GIS. The use of the latest technology or engineering marvel as a metaphor for human mind is standard strategy, whether the telephone switchboard, computer, or the hologram. Surely, virtual reality systems and even Star Trek's "holodeck" hold promise as new metaphors for the spatial mind.

Whatever its label, spatial knowledge about environments may be acquired from any of several different sources. The following is a comprehensive list of sources of spatial knowledge organized into four categories:

1. *Direct environmental experience.* Being the "original" source of spatial knowledge about the environment, and probably the most common and fundamental, people acquire a great deal of spatial knowledge about environments from direct experience in those environments. There are several variations that may have important implications for the nature of resulting cognitive representations. Does the experience include locomotion through the environment or just stationary viewing? If locomotion, is it mechanically aided (bicycle, wheelchair, car, plane, etc.) or not (crawling, walking, running, etc.)? Furthermore, it is important to realize that spatial properties of directly experienced environments are not just "seen". They are sensed multimodally: proprioceptively, auditorily, and perhaps other ways to lesser extents.

2. *Static pictorial representations.* These are the relatively small external representations which have long been used to store and communicate spatial information. They vary in their abstractness, from maps and diagrams to paintings and photos. We also include 3-D physical models as "quasi-pictorial" representations, as they suggest topography directly but are still primarily about a 2-D planet surface. And though most often designed for vision, pictorial representations are also available for the tactile and auditory modalities.

3. *Dynamic pictorial representations.* When changes in features or variables over time are depicted by movement, we can speak of dynamic pictorial representations. The variations described above for static representations apply here, including the possibility of dynamic 3-D models. Some dynamic representations are more map-like (animations), others are more experience-like (movies and videos). We consider the new technology of virtual reality (or virtual environments, etc.) as an increasingly important example of this last category. It constitutes a terrain-level simulation of direct environmental experience, viewed at the same scale as those environments.

4. *Language.* Finally, people often obtain spatial knowledge through language. It may be spoken or written (even sung—Chatwin, 1987). Sign-languages for the deaf and Braille

for the blind are special cases. Although natural language is most often the concern here, we include mathematical and gestural languages as well.

Like any taxonomic system, the categorization offered here is but one interpretation. Alternative organizations are possible that could highlight other characteristics. Any such system can be misleading, insofar as it suggests shared properties that do not hold. An important point not captured by this categorization is that multiple sources often operate, either simultaneously or sequentially. A critical set of research questions, still largely uninvestigated, relates to the integration or combination of multiple sources of spatial knowledge.

It may be more useful instead to focus on the factors that differentiate the myriad sources with respect to the cognitive/perceptual processes involved and the resulting knowledge structures. Here are several plausible candidates for such factors, several of which are suggested by our list of sources and by the papers that make up this special issue:

1. *Sensory/motor systems.* Sources vary with respect to the sensory systems involved. Possibilities include one or more of the following: vision, touch, hearing, kinesthesis, and vestibular sensing. Smell is less likely, and the existence of "magnetoreception" is questionable. In addition, motor systems that might be involved include everything from eye, head, and hand movements to climbing and walking. To the extent that the nervous system can monitor its own motor commands, "motor efference" can also provide knowledge about space.

2. *Static vs. dynamic information.* There are two ways in which the sources can vary in terms of a static/dynamic factor. Some sources depict dynamic information, information about change over time. In addition, some sources depict dynamic information statically, such as a map with arrows showing movement, while others depict it dynamically, such as through animation.

3. *Sequential vs. simultaneous acquisition.* The various sources differ with respect to whether they promote relatively simultaneous or sequential pickup of spatial information. A pictorial representation is a typical example of the former, language of the latter. However, this distinction should not be overstated, as it often is, because all spatial information pickup is sequential to some degree. Even simple viewing of a map or photograph occurs over time as the eyes scan from one place to another, foveating small areas for maximal resolution (Dobson, 1979; Yarbus, 1967).

4. *Symbols and their arbitrariness.* The interpretation of spatial and/or nonspatial information via some sources requires that symbols be translated. Symbolic representation occurs when a pattern or feature on a representation "stands for" something else. The location of objects in a room is nonsymbolically perceived when you are looking at them in the room, symbolically perceived when seen on a blueprint. But importantly, symbols vary in their arbitrariness/iconicity. This is essentially a question of the degree to which symbols resemble what they represent, their "referent". Relatively iconic symbols have shape or other properties that are similar to those of the referent. A USGS topographic map, for instance, represents 2-D location in an iconic way because places further away from a station point in the world are further away on the map, etc. Arbitrary symbols stand for their referent according to convention only. Contour lines on the topographic map represent elevation in a largely arbitrary way. Language represents spatial information in a completely arbitrary way.

5. *Scale translation and flexibility.* Given a symbolic source of spatial knowledge, a question is whether the space of the representation is at the same scale as the space of the referent. If not, the user will need to perform a scale translation to obtain some of the spatial knowledge available. Further, some sources that require scale translations will be flexible in allowing multiple scales to be shown, either simultaneously or sequentially with little or no lag time, perhaps at the user's discretion (with a well-designed computer mapping package). Although the question of scale typically focuses on space, time would also be an issue with dynamic representations. Is the change shown at the same speed as the actual event, or is it slower or faster?

6. *Viewing perspective.* Sources of spatial knowledge may be differentiated according to the perspective from which their spatial information is viewed. This includes the traditional vertical perspective of a map, the horizontal perspective of much terrestrial locomotion, and the oblique perspectives in between. Among other things, viewing perspective may influence the degree to which a person experiences space from the "inside" or the "outside" (as might the factors of scale and detail). The "internality" or "externality" of a source apparently has implications for the storage and processing of spatial knowledge in several ways, as some of the articles discuss. Although sources of spatial knowledge have historically allowed viewing from only a single perspective, modern technology holds the promise of allowing viewing from multiple perspectives just as it allows for multiple scales. Interestingly, viewing perspective is even a question for linguistic sources, as some of the papers below discuss.

7. *Precision.* Sources of spatial knowledge differ a great deal in terms of the precision with which they represent and communicate spatial information. Even when a spatial property such as location or distance is precise in the world, it need not be perceived or represented as precise. Probably the most important example of this is natural language about space. To say that "the bike is in front of the school" does not specify the bike's location very precisely, but it is a common way of speaking even when the speaker knows the bike's location much more precisely. It is important to remember that one does not always want to maximize precision in a knowledge source; efforts are sometimes made (or maybe should be) to reduce the communicated precision of the information. For instance, boundary representations on maps commonly mislead by suggesting a sharper separation than actually exists in the world.

8. *Inclusion of detail, some irrelevant.* Finally, sources of spatial knowledge vary a great deal in the degree to which they include details, possibly irrelevant. Much of the information we are exposed to as we directly experience environments is irrelevant to our understanding of spatial properties (or any useful properties). A photograph of a house contains more detail than a simple sketch of that house. Verbal navigation instructions ("directions") always leave out details about properties of the space that are not relevant to the purpose of navigation; unfortunately, they not uncommonly leave out relevant detail too. In addition, what is relevant varies from person to person.

OVERVIEW OF PAPERS

All of the papers in this special issue discuss characteristics of one or more of the sources of spatial knowledge described above. Focus is on comparisons between sources with respect to some of the differentiating factors just listed. The papers also emphasize empirical evaluation of the factors; all of the papers except Warren's present new research or reviews of existing research that incorporate behavioral science testing of human subjects.

The first paper, by Sholl, is entitled *The representation and retrieval of map and environment knowledge.* This is the first of two papers that focus on questions about map-acquired vs. directly experienced knowledge of space. Sholl discusses several ways in which the two sources apparently produce spatial knowledge with similar properties (orthogonal biases, hierarchical effects, etc.). However, information derived from the two seems to involve different coordinate systems when accessed from long-term memory (i.e., when thought about), retinocentric in the case of maps and body-centered in the case of directly experienced. Thus, the coordinate system used to retrieve information is proposed to be separate from the system used to store that information.

Presson's paper, *Orientation-specificity in spatial recall: Distinct spatial memories?*, also deals with questions of map-acquired vs. directly experienced knowledge of environmental space. He discusses the well-known distinction he has helped to develop between "primary" and "secondary" spatial systems. Several studies are reviewed that support the notion that map-acquired knowledge is stored in an "orientation-specific" way, according to the orientation seen during learning (for example, with north at the top). That is, questions answered with information remembered from a map will be much more difficult if they require an orientation of the map in other than the learned orientation. Directly experienced knowledge, on the other hand, is stored in a more flexible "orientation-free" way, even when it is learned from a single viewpoint.

The third paper is by Freundschuh and Mercer, entitled *Spatial cognitive representations of story worlds acquired from maps and narrative.* This is the first of two papers that deal with natural language about space. Research on the construction of "mental models" from narratives is discussed, including influential work by Bower and colleagues. This research suggests that spatial (i.e., nonlinguistic) mental representations of some kind are constructed in working memory when people think about events in stories or verbal descriptions. Freundschuh and Mercer present a study that investigates the robustness and generality of this phenomenon and raise the question of whether there are special conditions required to produce behavioral evidence for the construction of mental models.

The fourth paper is a review by Taylor and Tversky entitled *Assessing spatial representation using text.* They cover research investigating how environmental spaces are learned from verbal descriptions. Comparisons are made between linguistically-acquired, directly-experienced, and map-acquired knowledge. In the process, a concise overview of many findings from the spatial cognition literature is provided.

The fifth and final paper is Warren's *Maps and landscapes: Modes of spatial representation.* In this paper, he compares and contrasts maps and landscape paintings as means of representing physical environments. Various factors (scale, detail, abstractness, perspective) are described that contribute to a sense of being "internal" or "external" to the environment. Maps and landscape paintings are proposed to be at opposite ends of a multi-dimensional continuum that has implications for perceptual/cognitive processing of spatial representations.

What implications for GIS emerge from these five papers? The authors' charge was not to focus on any specific application, including GIS. As a matter of interest, only Freundschuh and Mercer are experienced GIS users. But we see several themes in these papers that have important implications for GIS. Maybe the most general and important, and one provided by all of the papers, is one none of the authors explicitly intended. The papers are written by behavioral scientists, but in a forum like the present one, they will hopefully be read by many non-behavioral scientists who we think can benefit from them. As such, these papers serve as examples of how behavioral scientists (particularly psychologists) think, what some of their concepts and vocabulary are, what methodologies are used and available, how behavioral data is processed and analyzed, and so on.

Otherwise, we can organize the relevant themes from the papers into three sets. All three are well summarized by a statement in the first paragraph of Taylor and Tversky's paper: "To be effective, GIS will need interfaces compatible with the way human beings absorb, represent, and use spatial information". The first set of themes comes particularly from the papers of Sholl and Presson. It concerns the nature of spatial information acquisition from maps and other pictorial representations (certainly including CRT maps) in comparison to acquisition from direct experience of the environments represented by the maps. What are the perceptual/cognitive consequences of different pictorial representations? Does the interpretation of spatial information from pictorial representations lead to special confusions or barriers to the use of the information for decision-making in real environments (such as planning, etc.)?

We suggest as a second set of themes some specific issues about the style of the pictorial representations generated by a GIS. The papers by Sholl, Presson, and Warren, suggest how important it is for GIS to allow for multiple scales and viewing perspectives in its representations. Optimally, these multiple views should be flexible, that is, easy to modify and combine by the user in idiosyncratic ways (intelligent defaults are a must, however). Zooming in or out, panning, and rotation functions should be easy and efficient. The question of what factor or factors is responsible for "alignment effects" is clearly central to basic theory—their specific consequences for GIS await investigation. And the possible utility in many decision-making contexts of systems that are able to quickly jump between or simultaneously depict horizontal and vertical perspectives is a ripe area for research and development.

A final set of themes deals with language, discussed in the papers of Freundschuh and Mercer, and Taylor and Tversky. How are linguistic queries understood in GIS, and how should they be designed? What verbal labels or commands should be supplied for spatial features, data layers, functions, etc. Or is it better to provide nonlinguistic icons, for instance, instead of words? How will linguistically communicated information mesh or otherwise interact with nonlinguistic information? How should language and pictorial representations be used in technical manuals? As these papers show, issues about language even have implications for the scale and viewing perspective questions described in the second set of themes above.

Because these five papers are about "sources of spatial knowledge", their implications for GIS deal almost entirely with the representational functions of GIS. This is not meant to imply that there are no other implications of perceptual and cognitive research for GIS. There is a need to understand how humans understand the procedures and concepts of GIS analytic and data processing capabilities too (Couclelis, 1992; Golledge, 1992; Mark, 1993; Mark & Frank, 1991; Peuquet, 1988). What are the fundamental spatial concepts humans use and understand? We believe this question has wide significance for many aspects of GIS design, education, social effects, etc. An important question yet to be answered, however, is whether we should concentrate more on modifying GIS for humans, or on training users to understand and use GIS effectively. Should GIS be developed to mirror human capabilities or to compensate for human limitations? The answer to these questions undoubtedly lies somewhere between these choices.

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