Chapter 14. Functions and Applications of Spatial Cognition

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In this chapter, we address the question of why it is important to study spatial cognition. Spatial cognition plays a central role in numerous human activities and helps solve numerous human problems. In other words, cognition of and with spatiality is both a fundamental component of human experience, and functional and relevant in many situations, both routine and exceptional. In fact, it is difficult to overstate the importance and even ubiquity of spatial cognition in mental and behavioral structures and processes. We discuss research on human spatial cognition with a focus on its functions in life activities and experiences. Then we discuss how studying spatial cognition can inform applications such as designing and evaluating personnel selection methods, training procedures, built environments, and various information tools and systems, such as mobile geographic information services.

Our goals in writing this chapter lead us to consider the essential meaning of spatial cognition. After all, it is impossible to say whether some task or activity involves or exemplifies *spatial cognition* unless we are prepared to offer a view on what is and is not spatial cognition. As most readers will suppose, this is no easy task, but we think the effort proves edifying. We start with the essential meaning of space and spatiality—its ontology, in the traditional sense of the philosophical study of metaphysics. Providing a clear, correct, and complete definition of space and spatiality is, of course, notoriously difficult to do, especially if we wish to avoid invoking space itself in the definition. After all, spatiality is pervasive and fundamental to existence and experience, as we suggested above. Recognizing these difficulties, we can define spatiality as the collection of all “extensional properties” of reality. In the sense we mean here, extensionality refers to the property of occupying space or having spatiality, which of course is circular. Spatiality is the property of reality that reflects the fact that everything is not at one location, a definition that is somewhat tongue-in-cheek but at least less circular. Alternatively, we can explicate the meaning of spatiality by listing a collection of spatial properties: location, size, distance, direction, shape, connectivity, overlap, dimensionality, hierarchy, and so on. But however we define spatiality, we probably do not want simply to classify any cognition involving spatial properties as “spatial cognition.” After all, one can make a good case that all cognition occurs in space and involves spatial information, at least implicitly. This includes linguistic, numerical, social, and other domains of cognition that we probably do not want to include as central foci of the study of spatial cognition. Thus, we can restrict spatial cognition to cognition that is primarily about spatiality—that serves primarily to solve problems involving spatial properties as a core component. As a contrasting example, reading requires spatial processing as part of orthography and syntax, but it is primarily about understanding written language, not solving a spatial problem (except when reading route directions, etc.).

A list of spatial properties is large and diverse, although not unlimited. One way to organize our understanding of spatial properties is in terms of their level of geometric complexity or sophistication. Especially since the nineteenth century, we have come to understand geometry as more than just Euclidean metric geometry (Sklar, 1974; van Fraassen, 1985). Alternatives include both non-Euclidean metric geometries and non-metric geometries such as affine, projective, and topological geometries. The appropriate geometry one should use to model human spatial cognition has been the subject of behavioral research in recent decades (e.g., Cheng & Newcombe, 2005; Dehaene, Izard, Pica, & Spelke, 2006; Golledge & Hubert, 1982; Hartley, Trinkler, & Burgess, 2004; Montello, 1992; Rinck & Denis, 2004). Clearly, spatial tasks do not necessarily require metric spatial knowledge, and in fact, can often be performed well without it. Evidence indicates that people often have a poor or nonexistent understanding of metric spatial properties, especially as it concerns larger “environmental” spaces. Conversely, evidence also shows that at least some people do acquire something like metric information of fairly high quality about the layout of environments (Ishikawa & Montello, 2006), even if it does not strictly obey the metric axioms.

In addition to the meaning of spatiality, we also delimit the scope of our discussion by considering what to include as *cognitive*. A broad definition of cognition includes both relatively low-level and high-level mental processes, both implicit and explicit processes, and processes that are both bottom-up and top-down. The domain of spatial cognition, as it has been studied in various cognitive disciplines, has tended to focus on relatively high-level tasks, such as those involving reasoning, communication, imagination, symbolic representation and interpretation, and the like—tasks that are thought to incorporate internally represented spatial knowledge that is potentially accessed explicitly. Work like this has excluded tasks requiring only perception-action coordination from the study of spatial cognition (of course, there are debates about how much “cognitive” processing is required for particular tasks). That is, deciding which door to walk through to get outside is a spatial cognition problem; moving one’s body to avoid running into the door jamb as you leave is not, notwithstanding that the latter is nontrivial and certainly involves psychological processing of spatial information. Although this distinction is imperfect, and might at times mislead us, we follow this approach in our chapter and delimit our scope by distinguishing the cognition of space from the perception of space and from behavior in space. We do not consider, except incidentally, spatial problems that are primarily perceptual and motor, such as object recognition or maintaining balance while walking.

Thus, we define spatial cognition as the area of research that studies activities centrally involving explicit mental representations of space (or at least potentially explicit).[1] We recognize this will still fail to satisfy some readers; we are not completely comfortable ourselves with this restriction. At the same time we recognize that many activities we would not want to include as spatial cognition have spatial cognitive components, we also see that most (all?) spatial cognitive tasks have non-spatial and non-cognitive components, or can be carried out in alternative ways that are not spatial (e.g., you can reconstruct and scan a spatial mental model or retrieve a verbal description of a situation) or particularly cognitive (you can reason how to get back to your car or simply ask your companion).

Functions of Spatial Cognition

To discuss the functions of spatial cognition is to discuss what spatial cognition is useful for. What tasks does spatial cognition contribute to in a significant way? We include both everyday tasks, such as choosing the right street to take while driving to the store, and specialized tasks, such as choosing the right vein area to examine while searching for tumors in a patient's liver. This is a large number of tasks taken individually, although they can be grouped into subsets for which spatial cognition clearly plays a similar role or contributes in similar ways to their successful performance. For example, interviews and observations summarized by Hegarty, Keehner, Cohen, Montello, and Lippa (2007) suggest that, like pedestrians in a neighborhood, surgeons and surgery residents use "landmarks" in the human body to remain oriented.

We consider functions of spatial cognition by listing categories of spatial cognitive tasks that people perform—everyday and specialized tasks that involve spatial cognition to a substantial degree (e.g., Eliot & Czarnolewski, 2007). In Table 1, we propose six categories of spatial-cognitive tasks.[2] Although we attempt to be comprehensive with our list, we are fairly confident it overlooks some things; for instance, we considered including reasoning about social space as a type. Furthermore, our attempt to formulate distinct categories notwithstanding, they clearly overlap, and we are skeptical that any fairly comprehensive list of functions could approach mutual exclusivity. Wayfinding sometimes utilizes spatial symbolic representations and spatial language, for example. The list is clearly only a starting point.

Our first category of tasks, wayfinding, is coordination to the distal environment, which is not immediately accessible to the sensory-motor systems. This contrasts with locomotion, which we consider as coordination to the proximal or surrounding environment (Montello, 2005; Strelow, 1985). Wayfinding includes specific tasks such as creating and choosing routes, establishing and maintaining orientation with respect to one's starting location or with respect to external features or places, recognizing how landmarks spatially relate to other landmarks or other aspects of the environment, judging distances, remembering sequences of turns, and remembering the locations of objects and events. Wayfinding includes planning multiple activities that are spatially distributed—that take place at different locations in the environment. Examples include sequencing multiple destinations, scheduling time to take account of travel requirements, and designing routes within complex path networks (e.g., Gärling & Gärling, 1988; Golledge, 1995). The role of spatial cognition in wayfinding differs somewhat as a function of movement modality (walking, driving, eye movements, etc.) and the spatial entity in which it takes place (a city, one's bedroom, the human body, a complex molecule, or a virtual environment). No matter what scale of space we wayfind in, however, a critical task is to establish and maintain a *sense of orientation* while moving—where are we or where is some entity in the world relative to some other location, such as the location of another entity or our own previous location.

-- Table 1 about here --

The second category of tasks on our list is acquiring and using spatial knowledge learned directly, that is, from perceptual-motor experience in the world. This occurs at figural, vista, and environmental scales of space. At figural scales, vision and haptics are the most important sensori-motor systems involved in spatial learning by humans. Vista-scale learning depends almost entirely on vision, and head and eye movements. Spaces at environmental scales require considerable body locomotion for their direct apprehension; thus visual and proprioceptive senses are of principal importance. At environmental scales, we learn about the locations of prominent features (landmarks), path network structures that connect places, and spatial relationships among places, even those we have not directly traveled between. At all scales, we learn spatial properties at all levels of geometric sophistication, including connections, containments, sequences, distances, directions, shapes, configurations, and so on. This knowledge is acquired both intentionally, during exploration, and incidentally, while we are otherwise carrying out goal-directed tasks such as travel.

Our third category of spatial tasks is using spatially iconic symbolic representations. These are graphical and volumetric symbolic representations that represent spatial and non-spatial information via their own spatial properties (and sometimes their temporal and thematic properties). Spatial cognition can be involved in both producing and interpreting these external representations. By definition, spatial learning at miniscule and gigantic scales occurs only via symbolic representations (we do not learn the relative locations of cities in Africa from direct experience but from examining maps), but of course, all scales of spaces are sometimes learned in this way. Two-dimensional (graphical) symbolic representations include maps, graphs, drawings and diagrams (including blueprints), photographs, movies, and other “pictorial” representations. Three-dimensional (volumetric) symbolic representations include physical models and globes.

The cognition involved in producing and interpreting different symbolic representations can vary quite substantially from one to another. For instance, cartographic maps depict a portion of the Earth’s surface, diagrams typically depict architectural or object spaces, and graphs usually use space metaphorically to depict nonspatial relationships (such as quantitative magnitude) (Tversky, 1997). Even within each type, there is a large amount of variation in how these representations depict information, what information they depict, how they are used, and more. For instance, maps may be reference maps or thematic maps, they may be used for navigation or for learning world geography, and they may depict metric information like distance accurately or distort metric information in order to focus on relationships such as connectivity and sequence. Recently, multivariate representations of very large data sets called *spatializations* have been generated that use landscape depictions to represent nonspatial information metaphorically (Skupin & Fabrikant, 2008). Research by Fabrikant and her colleagues (e.g., Fabrikant, Montello, Ruocco, & Middleton, 2004) has looked at the spatial reasoning involved in interpreting spatialized displays.

Our fourth category of spatial tasks is using spatial language, a non-iconic form of spatial symbolic representation system (see Taylor & Brunyé, this volume). Natural languages describe or instruct about space and spatiality abstractly; they exploit semantics (i.e., word, phrase, and sentence meanings) to communicate spatial properties of individual entities and relations among entities. Of course, there are substantial differences between the psychology of graphical and volumetric representations and that of natural language representations, although in the case of spatial descriptions, they may contain surprisingly similar spatial information content. For instance, Tversky and Lee (1999) found that routes depicted in sketch maps and described verbally similarly included particular landmark features, segmented the environment, and schematized elements such as curves. The way spatial information is encoded and communicated via language is studied in the context of tasks such as describing scenes and giving verbal route directions (Allen, 1997; Bloom, Peterson, Nadel, & Garrett, 1996; Jarvella & Klein, 1982). Researchers are interested in issues such as the precision or vagueness of spatial language, the absence or inclusion of landmarks in route directions, how *deictic* references convey spatial information, cross-linguistic differences and similarities in spatial language and thought, and more. But several prominent theories of language and thought have come to accord spatial thinking a central role in interpreting linguistic expressions in the first place, whether its semantic content is spatial or not. That is, spatial cognition has come to be recognized as essential to nonspatial thinking and communication with language. For instance, the theory of image schemata (Johnson, 1987) proposes that language is interpreted via the metaphorical extension of a few basic iconic mental representations to capture all semantics. Gentner and her colleagues have discussed the role of spatial thinking in temporal thinking and in the spatial alignment of conceptual structures during analogical reasoning more generally (Gattis, 2001; Gentner & Medina, 1998). The geometric theory of conceptual spaces (Gärdenfors, 2000) proposes that concepts are mentally represented as iconic representations whose geometric properties express relational meaning. Such iconic spatial theories of the psychology of semantics are, in fact, consistent with the effort described above to use iconic external representations called spatializations to communicate nonspatial information.

Our fifth category involves imagining places and reasoning about them with mental models, spatial mental representations constructed in working memory. Mental models are apparently constructed as part of interpreting narratives in language (Johnson-Laird, 1983). But they are also constructed from non-linguistic sources, such as direct experience with entities at figural, vista, or environmental scales (Hegarty & Just, 1993). They are even constructed out of imagination, and can represent spatial entities that a person has never directly experienced in any way. Thus, it is sensible to talk about reasoning with mental models of fictional entities that do not exist.

Our sixth category is location allocation, which is finding optimal or adequate locations for putting facilities such as retail businesses, hospitals, and schools. Locations are identified that minimize or reduce various relative cost functions, including traveled distance, that result from putting facilities in particular locations. This task is often handled non-cognitively now, by algorithmic and heuristic computer routines that do not mimic human cognition. But before location-allocation was formalized as a computational task, people attempted informally to locate facilities in an adaptive manner. This was a very intensive cognitive task that incorporated a great deal of spatial thinking. For example, in pre-industrial times, when siting a house, a person would need to consider factors such as the daily path of the sun, distance from water, distances from relatives, location within agricultural fields, safety from wild animals or other mobile threats, and so on. But even today, decisions such as picking a place of residence, a school, or a job, require spatial thinking that can be quite challenging. One must still consider factors such as the distance from one’s job, from one’s friends or family, from schools one’s children might attend, from public transit, and so on. Individuals rarely if ever use formal technologies and analytic methods to solve these problems, as cognitively challenging as they are.

Applications of Spatial Cognition

In the first part of our chapter, we provided an overview of various functions of spatial cognition. This overview demonstrates that spatial cognition plays a major role in our daily experience and activities, and that it helps solve various problems we encounter both regularly and occasionally. Clearly then, understanding spatial cognition should have application in a variety of practical domains (Allen, 2007; Golledge, 2004), involving objects and environments, as well as external spatial representations such as maps, graphs, linguistic descriptions, and more. The advent of digital media such as GPS-enabled navigation systems is providing new applications for spatial cognition. In this section, we selectively highlight and describe some important application areas of spatial cognition research (Table 2). This list is very definitely not comprehensive. We can see potential applications for spatial cognition research in a variety of other areas, such as forensic psychology, clinical and counseling psychology (disabilities, Alzheimer's and other syndromes), athletic training, aviation psychology, transportation and transit engineering, video gaming and digital communities, and more.

Before turning to specific application areas, a general point is warranted about applying research findings in spatial cognition. The experimental tradition in research manipulates variables in order to explore ways that varying stimulus materials, task settings, and other external factors influence the mental and behavioral responses of individuals. Of course, no two individuals are exactly alike, and that applies to virtually every aspect of spatial cognition (Hegarty & Waller, 2005). Furthermore, although researchers in the comparative tradition often explore these differences in terms of aggregate factors that differentiate people, such as age, sex, and culture, we can ultimately identify differences at the level of the individual (see Casey, this volume). That is, we can distinguish three levels of user parameters for system design and other purposes: generic, group, and individual (Raubal, 2009). The *generic* level covers the general set of cognitive parameters assumed to be applicable to all people. For example, people in general use landmarks for finding their way and for communicating wayfinding directions to others. *Groups* of users can be defined by common sets of cognitive parameters, such as similar abilities, interests, concerns, goals, beliefs, or behavioral practices. This results in various overlaps between different groups of users. Examples are gender groups, such as all women or all men, and cultural groups defined, for example, by sharing a common language. An important question for the design of cognitively engineered technology is what kinds of differences should be taken into account when forming a group of users within a particular spatio-temporal context. Wayfinding instructions, for example, need to be adapted for specific groups in order to be most useful. On the *individual* level every single person is ultimately different. Although personalization can potentially go a long way, the more parameters that need to be adapted, the more difficult and complex personalization becomes. For example, location-based services must represent individual user preferences, such as “I want to go from location X to location Y by public transport.” So all people share some cognitive parameters but they also fall into various “user groups” and have their individual preferences. Thus, we strongly advocate the need to consider group and individual variations when applying spatial cognition. It is also critical to explore the domain-generality and consistency of differences; to what tasks or skills does a particular difference apply, and how consistently? An informative discussion of these issues can be found in Appendix C of the report by the Committee on Support for Thinking Spatially (2006).

<Insert Table 2 Here>

Location-based services (LBS). Over the last decades, developed societies have become mobile information societies with the proliferation of spatial technologies. Such technologies comprise geospatial tools and services that support people in making spatio-temporal decisions. Finding one's way from the airport to a hotel in an unfamiliar city can be a demanding task that requires utilizing different cognitive abilities in the context of space and time. Location-aware technologies and location-based services (LBS) support users during such mobile decision making. They are sensitive to the location of a mobile person, having global positioning system (GPS) technology built into them, and relate the person's location to the surrounding environment via a geographic information system (GIS) database. This in turn allows the system to provide location-based information in the form of written instructions or cartographic maps that facilitate the successful completion of spatio-temporal tasks. The widespread adoption of LBS has resulted in tremendous benefits for their users by providing them with real-time spatio-temporal decision support for purposes ranging from the trivial (e.g., friend-finder services) to the critical (e.g., emergency response).

Highly important for this process of information seeking and decision making is the notion of *geographic relevance*, defined as "a relation between a geographic information need and the spatio-temporal expression of the geographic information objects needed to satisfy it" (Raper, 2007). That is, the system works well only when it is capable of organizing and filtering information according to the needs of a user. Achieving geographic relevance requires one to consider cognitive abilities and strategies people bring to the spatial problem-solving process. This is the goal of *spatial cognitive engineering*: to design spatial information systems and services based on principles of human communication and reasoning (Raubal, 2009; Taylor, Brunyé, & Taylor, 2009). It is an interdisciplinary endeavor, involving the disciplines of geographic information science, cognitive science, computer science, and engineering. A special focus is put on human-computer interaction based on the integration and processing of spatial and temporal aspects of phenomena. This includes various conceptualizations of space and time, matching spatial and temporal concepts between users and systems, effective communication of information, and qualitative methods of spatial reasoning and decision making that more closely mimic human thought.

Digital navigation services are the most successful and widely adopted category of LBS to date. They support users in finding optimal routes while driving, biking, or walking; they communicate through maps and verbal turn-by-turn instructions; and their maintenance is low (given that up-to-date street network data are used). Navigation services for pedestrians are generally more difficult to implement because pedestrians are not bound to a street network. These services strongly need personalization. For example, route instructions for people in wheelchairs must not include segments with stairways. These days, more and more of these services integrate landmarks because it has been realized that route instructions that rely mainly on quantitative values, such as "go straight for 1.5 km, then turn right, go 0.8 km" are difficult to follow while being on the move. Cognitive research has shown that providing landmark-based instructions, such as "turn right after the 6-story building" or "go straight until you reach In-N-Out Burger"[3] facilitates navigation for most users, at least in many situations (Denis, Michon, & Tom, 2007). Consequently, a research focus has developed that investigates methods for the automatic detection of landmarks to be used in wayfinding instructions (Sadeghian & Kantardzic, 2008). Spatial cognition research continues to contribute to developing better navigation services that incorporate landmarks people perceive, find salient, and readily identify.

Navigation services are often a part of *mobile guides,* which are portable and location-sensitive digital guides that provide an abundance of information to travelers and tourists. They have been slowly replacing traditional guide books and paper maps. Recently, several innovative LBS applications have emerged, and some of them focus on the integration of small mobile displays and large static paper maps. An illustrative application is *WikEar* (Schöning, Hecht, & Starosielski, 2008) (Figure 1), which integrates different perceptual modes (visual and auditory) and generates customized location-based guided tours by mining data from Wikipedia (www.wikipedia.org). These data are automatically organized according to principles from narrative theory (from cognitive science and semiotics) and integrated into an educational audio tour that starts and ends at stationary city maps.

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Different media can be utilized for communicating location-based and navigation information. Maps have been the most prominent medium, but several cognitive research issues arise when using maps on cell phones and Personal Digital Assistants (PDAs). Mobile displays are limited in size and resolution compared to larger screens, which makes map reading more difficult for the average user (Dillemuth, 2005) (and mobile devices are often used in situations of divided attention!). Maps are traditionally aligned on the display with north facing up. Just as users of traditional analog maps often turn the map as travel direction changes, users of mobile devices typically prefer digital maps to maintain “track-up” alignment (Aretz & Wickens, 1992). Sensor-based information can be used to determine a user’s direction of movement and automatically provide track-up oriented maps on mobile devices. Mobile map adaptation based on the user’s preferences, task, and location, among other context parameters, can help reduce both user interaction with the device and cognitive load for the user. For example, when the user reaches a decision point during a navigation task, the service can automatically zoom in to local detail (Raubal & Panov, 2009). For several applications—notably, navigation services—maps are often complemented or even substituted by verbal instructions (Streeter, Vitello, &

Wonsiewicz 1985). The benefit for car drivers is that they can keep their eyes on the road while listening to and following route instructions. Other graphic and pictorial aids, such as arrow graphics or scene photographs, can facilitate the transfer of wayfinding instructions to a traveler's surrounding environment by directing travelers to pertinent information and by depicting the environment in a less abstract way (Hirtle & Sorrows, 1998).

Geographic and other information systems. Spatial cognition research is relevant to spatial information technologies besides LBS. Generically, geographic information systems (GIS) are computer-based systems for storing, processing, and visualizing geographic information (Longley, Goodchild, Maguire, & Rhind, 2011). Their applications are manifold, including resource management, land-use planning, environmental monitoring, transportation, health, emergency management, and geomarketing. GIS have also been used to simulate human behavior in space, such as modeling lost person behavior and managing the search for lost persons (Heth & Cornell, 2007). By simulating individual wayfinding strategies for particular persons within representations of real-world environments modeled with GIS data, these systems can aid search planners and, through the use of mobile devices, search-and-rescue workers in the field.

Spatial cognition can potentially contribute to improving the effectiveness, efficiency, and usability of GIS in many ways (Hoffman & Markman, 2001; Mark, Freksa, Hirtle, Lloyd, & Tversky, 1999; Montello, 2009), especially with regard to the different ways users and systems interact. The design of GIS should benefit from considering how individuals understand and represent space (Medyckyj-Scott & Blades, 1992). For example, it has been suggested that spatializing user interfaces consistent with the spatial concepts and experiences of users will facilitate human-computer interaction in GIS (Kuhn, 1996). The metaphor of navigation can also be applied to other domains, including the Internet and other information systems that are not explicitly or directly geographic. For example, topologic and metric relations have been used to represent neighborhoods of related web pages and the distances between them, with web pages serving as information “landmarks.” In this way, navigation in electronic spaces can be supported by applying what we know about real environments and human interaction with real environments (Hirtle & Sorrows, 2007).

Information display. Information displays are patterned graphical representations, usually apprehended visually, that symbolically communicate information about something (Card, MacKinlay, & Schneiderman, 1999). Displays often communicate spatial information iconically, by using their own spatial properties to represent spatial properties of information content. An example would be a typical cartographic map, which represents distances in the world via distances on the map display. Displays also communicate spatial information abstractly, by using their own spatial properties to represent non-spatial properties of information content. An example would be a graph, which might use height on the graphic space to represent magnitude in an information set (of course, information displays also use many non-spatial properties to represent information content). Computer technology has allowed the development of interactive displays, which can be modified on the go by users who wish to create more customized looks at information. Animations add dynamic properties to the static properties of traditional displays, in order to use changing spatial and non-spatial properties of displays to represent spatial, temporal, and thematic properties of information. The metaphorical representation of non-spatial information via spatial properties of displays can be taken much further, by using complex and realistic visuo-spatial structures, such as natural or urban landscapes, to facilitate knowledge discovery in very large and complex information sets, relying for instance on principles like the “distance-similarity metaphor” (Fabrikant, Montello, & Mark, 2010; Fabrikant et al., 2004). This principle states that more similar entities should be placed closer together when represented in a display, because users will interpret closer entities as being more similar.

It has been recognized for nearly a century that spatial cognition research might contribute to producing better displays and to training people how to use them (Montello, 2002; Trickett & Trafton, 2006), and that display tools should provide representations that are consistent with and support human cognition (MacEachren, 1995). A cognitive approach to information visualization brings individual perception, understanding, and decision making to the design process, for example, providing a theory that explains why particular symbol shapes work or do not work for users. Modern displays, with their increased multivariate information and interactivity, make this even more true (Slocum et al., 2001).

Architecture and planning. As with information displays, it has been recognized for some time that architecture and planning are essentially environmental design for people, and understanding human characteristics should help design more effective environments (Carlson, Hölscher, Shipley, & Dalton, 2010; Evans, Fellows, Zorn, & Doty, 1980). Effective environments might be easy to orient in, lead to an appropriate level of privacy or sociability, appear interesting without being too confusing, induce feelings of safety, and so on. Spatial cognition is being applied to all of these issues, either at the time an environment is originally designed and built, or later, when attempts are made to improve the usability of environments already constructed.

Clearly, the visual and structural characteristics of environments make it easier or harder to establish orientation while navigating (Montello & Sas, 2006). Weisman (1981) identified four physical variables of environments that affect orientation: signage, differentiation of appearance, visual access, and layout complexity. All of these variables apply to built environments like buildings and cities, and the first three apply to natural environments like wilderness areas as well. These variables influence the perceptibility and salience of features in the environment, the memorability of features and spatial relations among features, the ease of updating as one travels about, and the applicability of different strategies for wayfinding. In fact, their importance is even broader, influencing where people are able or allowed to move, how they respond affectively to places, the ease or difficulty of particular kinds of social interactions, and more.

With respect to signage, research shows that signs are more effective when they are well designed and placed at decision points during travel; conversely, poor signage can certainly confuse (e.g., Arthur & Passini, 1992). The disorienting effect of misaligned "You-Are-Here" maps (which can be considered as a type of signage) is one of the most robust and well-known phenomena in spatial cognition research (Klippel, Hirtle, & Davies, 2010; Levine, 1982). Differentiation of appearance is the extent to which different parts of the environment look similar or different from each other, in terms of size, form, color, architectural style, and so on. Environments that are more differentiated generally make orientation easier, but too much unorganized differentiation can become illegible and confusing. Visual access is how far one can see in different directions from different places (auditory access is of some relevance, too). It depends on the environmental shape created by opaque structures, but also on topography and atmospheric conditions when outdoors. It also depends on a viewer's position and other characteristics (height, visual acuity). Environments with more visual access generally make orientation easier. *Isovist analysis* provides a method for spatial cognition researchers to measure visual access in different places (Benedikt & Burnham, 1985). An isovist is the collected spatial extent of all views, or “vistas,” from a single place within an environment.

For spatial cognition researchers, layout complexity is probably the most interesting and subtle of Weisman’s four variables. It involves the shapes or patterns of rooms, halls, path networks, clearings, and so on. Environments with less layout complexity generally make orientation easier. But determining layout complexity is not always straightforward and is an ongoing research issue. Cognitive researchers must be part of this effort, as complexity is not simply an objective matter to be analyzed, for example, by information theory (e.g., Attneave, 1959). Of concern to cognitive scientists is what makes a layout complex to a person, not just complex mathematically or logically. A variety of factors probably influence subjective complexity, including the overall size of a layout, the orthogonality or obliqueness of turns and intersections (Werner & Schindler, 2004), and the degree of articulation of sub-spaces, like hallways or rooms. Some environmental shapes have better form (as in the Gestalt concept of *Prägnanz*) and are probably easier to comprehend, remember, and verbally describe; in fact, layouts appear to be cognitively distorted toward good form (Tversky, 1992). A very promising approach to studying layout complexity and spatial cognition is the theory and method of *space syntax* (Penn, 2003). Space syntax is a formal language for describing and measuring properties of layout, especially network patterns and interconnectivity. It simplifies place layout by identifying “pieces” that can then be related in terms of topology, specifically the sequences of connected nodes linked in abstract graph structures. These pieces can represent convex subspaces, or straight-line axes of movement or vistas.

Personnel selection. Spatial cognition research can help to select people who will more likely succeed at a particular activity or career. Personnel selection has been a primary aim of spatial-test development since its inception in the 19th century (Eliot & Smith, 1983). If an activity requires spatial thinking for its successful completion, then people who think better spatially should be more likely to succeed at it. In fact, tests of spatial thinking have been used to select from applicants to dental and medical school (Hegarty et al., 2007). Of course, general aptitude tests such as the SAT and GRE include spatial thinking items, although these items are typically aggregated with nonspatial logical and mathematical items when used to make admissions decisions.

Although the validity of using measures of spatial abilities to select personnel would hold to some degree no matter the genesis of ability differences, it would be more useful to do so if the differences are relatively less modifiable by training or other experiences. Although innate abilities are not necessarily immutable, they may be less easily improved than those resulting from experience, especially relatively short-term experience. In fact, as Hegarty et al. (2007) discuss in detail, there is a considerable debate in the medical education field about whether the abilities involved in learning anatomy, performing surgery, and so on, are relatively changeable or not (e.g., Gilligan, Welsh, Watts, & Treasure, 1999; Wanzel et al., 2003). If they are, it would probably be misguided to reject applicants with lower scores on those abilities, as they may be able to achieve adequate levels of performance on relevant tasks with particular types or amounts of experience. In their review, Hegarty et al. (2007) concluded that "high-spatial" students have an advantage early in medical training, but that all students who are otherwise qualified will likely be able to acquire necessary skills involving particular types of spatial ability; the relationship of ability with success at mastering medical skills diminishes with training and practice.

Finally, we note that it is important that researchers and practitioners do not restrict themselves to the notion of a unitary, monolithic "spatial ability." Instead, we should continue to refine our understanding of not only “components” of spatial thinking in the traditional psychometric sense, but of task and situation contexts in which different types of spatial thinking are important. We will best be able to predict how well people perform some spatial task if we develop a detailed understanding of the specific knowledge structures and processes involved in performing the task (e.g., Hegarty & Waller, 2005). An example is the apparent difference between reasoning at figural and environmental scales. As another example, the predictors of success at reaching a destination in a timely manner during travel will be rather different for people who conceive of an environment as a collection of one-dimensional routes than for people who conceive of it as a two-dimensional layout (Devlin, 2001).

Spatial education. Closely related to using spatial cognition research to help with personnel selection is using it to improve education in spatially-intensive disciplines and occupations. Many occupations and avocations involve spatial thinking quite centrally, and research in spatial cognition is being applied to designing and evaluating education programs and procedures in these fields (Hsi, Linn, & Bell, 1997). Although people differ in their spatial cognitive abilities, evidence shows that such abilities are trainable, at least to some extent (e.g., Lohman & Nichols, 1990; Newcombe & Frick, 2010). In most domains, spatial thinking concerns both the phenomenon of interest and symbolic representations of the phenomenon, such as maps, diagrams, and models. Examples of academic and scientific fields for which spatial education is likely to be useful include geography (Gersmehl & Gersmehl, 2006; Marsh, Golledge, & Battersby, 2007) and earth sciences (Kastens & Ishikawa, 2006; Plumert, 1993), mathematics (Bishop, 1980), and medicine and dentistry (Hegarty et al., 2007). Education in spatial cognition can also apply to many non-academic endeavors, such as carpentry or taxi driving (Maguire et al. 2000).

Several researchers and educators have pushed for the incorporation of technologies like GIS and CAD (computer-aided design) into the classroom at all grade levels, on the grounds that such technologies fundamentally entail spatial thinking and will therefore foster more and better spatial thinking (Albert & Golledge, 1999; Committee on Support for Thinking Spatially, 2006). However, as we discuss in our conclusions below, spatial technologies usually work largely by replacing spatial thinking, rather than enhancing it. In many cases, for instance, the technology turns a thinking problem into a perception problem—I enter a command and then read the answer off a screen. That reservation aside, we agree with the recent recognition that spatial thinking is fundamentally important in many areas of life, and that it is under-recognized and under-instructed in education programs. In addition to the 2006 report of the Committee on Support for Thinking Spatially we have already cited, see the *Spatial Intelligence and Learning Center*, http://www.spatiallearning.org/; the *Center for Spatial Studies*, http://spatial.ucsb.edu/; and *Spatial Literacy in Teaching*, http://www.le.ac.uk/gg/splint/.

Summary and Future Prospects

In this chapter, we have reviewed conceptual ideas and empirical results that focus on functions and applications of spatial cognition. We hope that our review stimulates further questions and future research directions. In particular, we appreciate that many questions remain about the role of spatial cognition research in the development of spatial technologies, and about the appropriate use of spatial technologies and their ultimate implications for human life and experience. By now, as we have briefly discussed, there are several demonstrations of successfully applying spatial cognition research to a variety of problem areas, including aspects of the design of information systems (whether specifically for navigation, search and rescue, or more generally), the design and redesign of architectural spaces, the use of spatial tests for student selection, and the development of education programs in spatial thinking. Nonetheless, we consider it an ongoing question as to what degree research in spatial cognition can improve the functionality of technology, and if so, how. For members of the spatial cognition community, like ourselves, belief in the practical usefulness of such research is almost a matter of faith. In fact, there are not that many clear demonstrations of this, and there are some reasons to question it. For instance, should navigation systems present maps and verbal directions that mimic human thinking (e.g., Tversky & Lee, 1999), or do we accept that tools and technologies are useful precisely because they do not mimic the limited memory of humans, limited quantitative precision and accuracy, limited reasoning complexity, and so on?

The great benefits of spatial technologies are evident, such as in emergency situations where lives are saved. As spatial technologies become more common in societies around the world, however, it is worth contemplating what negative effects they may have. Will our navigation systems make us spatially witless, anti-social, or otherwise less happy and healthy? We have arguments and evidence that using such systems places higher visual and cognitive demands on the driver (Burnett, Summerskill, & Porter, 2004). In the long run, we think it is likely that the regular use of GPS-enabled navigation systems will diminish people's ability to maintain orientation by using old-fashioned perceptual-motor and cognitive systems. Research is starting to verify this (Ishikawa, Fujiwara, Imai, & Okabe, 2008; Parush, Ahuvia-Pick, & Erev, 2007). This technological "infantilization" is admittedly nothing new. Celebrated feats of pre-technological orientation such as the navigation systems of the Micronesians (Gladwin, 1970) do not result from some "innate primitive intelligence," but on training, practice, and focusing attention on particular details in the world. Our own navigation technologies and environmental modifications partially replace these psychological skills and tendencies with structure and information that do much of the cognitive work for us. Similarly, one can wonder if the drive to integrate spatial technologies like GIS into educational settings will end up replacing thinking rather than enhancing it.

We also note that the widespread use and distribution of LBS has led to concerns about people's trust in the information provided by these services; several accidents have been reported which occurred partly because of gullibility about the accuracy of the systems. The question of what factors influence the credibility of information displays is partially a question for spatial cognition researchers (e.g., Smallman & St. John, 2005).

In sum, we believe that addressing issues about spatial technology and cognition would benefit from more studies of how people actually use navigational technologies in daily situations. We recommend that researchers and developers consider how to adapt technology so users achieve immediate *and* longer-term objectives. Can travelers get to their destinations safely and efficiently, at the same time they learn more about their surroundings, not less? That is, can technologies provide functionality but also enhance spatial cognition by integrating cognition in the head with cognition in the world (Norman, 1988)?

Suggested References for Further Reading

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Allen, G. L. (Ed.). (2007). *Applied spatial cognition: From research to cognitive technology*. Mahwah, NJ: Lawrence Erlbaum. Recent edited collection that is the most focused and comprehensive discussion of applications of spatial cognition, including in the areas of wayfinding, visualization, architecture, information system design and training, managing search for lost persons, military training, and medical training.

Committee on Support for Thinking Spatially: The Incorporation of Geographic Information Science Across the K-12 Curriculum, N. R. C. (2006). *Learning to think spatially*. Washington, DC: National Academies Press. Report by a multidisciplinary committee, organized and supported by the U.S. National Academies, which discusses widely ranging functions and applications of spatial cognition in earth and environmental sciences, social sciences, and other disciplines; its Appendix C on “Individual differences in spatial thinking: The effects of age, development, and sex” is one of the best concise pieces available on the subject.

Hirtle, S. C. (2011). *Geographical design: Spatial cognition and geographical information science*. San Rafael, CA: Morgan & Claypool Publishers. Recent overview of applications of spatial cognition in the field of geographical information science that is deeply informed by spatial cognition research and theory across the disciplines of psychology, geography, and computer and information science.

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Newcombe, N. S., & Huttenlocher, J. (2000). *Making space: The development of spatial representation and reasoning*. Cambridge, MA: The MIT Press. Recent summary of theory and research on spatial cognition, particularly its development in infancy and childhood; includes cognition based on direct environmental experience and cartographic

maps.

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Footnotes

1. Like the referents of verbs, we do not restrict activities only to situations involving movement of all or part of one’s body; they include states of being, such as contemplating or sleeping.

2. Reg Golledge provided special insight and inspiration in developing the list of spatial tasks. The list has also benefited from discussions we have had with Karl Grossner, Mary Hegarty, and Andrea Nuernberger.

3. This is a regional chain of fast food restaurants with locations in the western United States. Palm trees planted to form an *X* in front of the restaurants add to the “landmarkness” of the sites.

Table 1

Tasks Involving Substantial and Significant Spatial Cognition in Their Performance

1. Wayfinding as Part of Navigation
2. Acquiring and Using Spatial Knowledge from Direct Experience
3. Using Spatially Iconic Symbolic Representations
4. Using Spatial Language
5. Imagining Places/Reasoning with Mental Models
6. Location Allocation

Table 2

Some Important Application Areas for Spatial Cognition Research

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A. Location-Based Services (LBS)

B. Geographic and Other Information Systems

C. Information Display

D. Architecture and Planning

E. Personnel Selection

F. Spatial Education