1 Concepts for Spatial Learning and Education: An Introduction

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This book discusses concepts and conceptualization relevant to the emerging field of spatial learning and education. Spatial learning and education is learning and education about (and with) space and spatiality, both informally and in formal educational settings, such as those involving classrooms, textbooks, or workbooks for K–16 education (that is, from kindergarten to a bachelor's degree). The three of us share a professional interest in space and spatiality as central components in understanding the natural and cultural worlds, as well as the abstract or metaphorical worlds of art, literature, and mathematics. Furthermore, we believe that promoting spatial thinking in educational curricula is worthwhile and that intellectual questions about such a profound property of reality—so concrete and pervasive yet so abstract and suited to metaphor—are utterly fascinating. We recognize there is increasing interest across several disciplines and problem domains in the role of space and spatiality in thinking, learning, reasoning, and communication, and in the possibility of explicitly educating students about space and spatiality (Liben 2006; National Research Council 2006; Newcombe and Frick 2010). There has recently occurred what has been termed a "spatial turn" in many disciplines (Bodenhamer, Corrigan, and Harris 2010; Dear, Ketchum, Luria, and Richardson 2011; Goodchild and Janelle 2010; Scholten, van de Velde, and van Manen 2009; Warf and Arias 2009), quite possibly motivating a desire to develop educational curricula specifically focusing on spatiality. This spatial turn may also have encouraged an emerging focus by researchers and educators on understanding spatial conceptualization, language, learning, and problem solving more generally, across various academic and non-academic contexts. In this introductory chapter, we draw on the emerging interest in spatial thinking and (1) set forth the intellectual context of ideas and challenges that have guided the editors and chapter authors, (2) present problems associated with spatial-concept learning and education, (3) pose opportunities for advancing research on spatial concept understanding and use, and (4) present an overview of the book's content, highlighting how the authors of specific chapters augment our understanding of spatial thinking in different disciplines and contribute to spatial learning and education.

We believe this education focus on spatiality should be informed by the various research activities involving spatial thinking and reasoning that have been ongoing for several decades in such research fields as spatial cognition, geographic information systems, spatial econometrics, spatial humanities, data visualization, and other areas of innovation. We see obvious connections among the goals of these different communities, but they have been fairly separate thus far. We believe that bringing them together and exploring similarities and differences among their work will potentially benefit them all. We especially support the idea that effective spatial education must be based on a thorough understanding of how people conceptualize and learn space and spatiality in a broad range of problem domains, including design, communication, optimization, navigation, and others that relate to daily-life experiences and behavior and to spatial tasks associated with different professions.

Spatial learning and education pose definite intellectual and empirical challenges for researchers and educators. Its multi-disciplinary nature makes communication across disciplines confusing at times, with multiple terms and frameworks that are not easily translated or that are used differently by different communities. The tension between empirical and theoretical approaches (possibly most pronounced in comparing the humanities and the sciences, and in the sometimes incompatible goals of basic and applied research) is particularly challenging for this area, in part because spatiality is so ubiquitous but also so abstract. It has often been noted that simple, unambiguous definitions of terms such as "spatial thinking," "spatial learning," and "spatial intelligence" are hard to come by; just defining "spatiality" in the first place without invoking space is infamously difficult, as we consider further below. But at the same time we recognize these challenges, we want to develop education programs that enhance "spatial literacy" (itself an ambiguous term). Furthermore, a correlation between spatial reasoning skills and educational and professional performance in many scientific and technological fields has been demonstrated. If spatial intelligence or spatial thinking ability can be improved in the course of education and/or professional practice, where and how will it happen in the contexts of educational curricula and professional development? Although the editors and chapter authors offer evidence and speculate on possible answers to this question, readers are encouraged to approach

these findings and suggestions with a critical mind, recognizing that there remain substantive research and institutional challenges to effective implementation of spatial curricula for education and lifelong learning. In the balance of this introduction, we address (1) questions about the meaning and possible interpretations of space and spatiality, (2) the importance of spatial concepts and conceptualizations, and (3) the case for spatial learning and education.

What Are Space and Spatiality?

We consider first the thorny problem of defining space and spatiality (Sklar 1974; van Fraassen 1985). It is thorny in part because space and spatiality is ubiquitous in experience and reality. Avoiding circularity in the definition is therefore quite difficult, perhaps impossible. The circularity is evident in any dictionary definition, where one finds "space" in the general sense we mean here—much broader than the common lay use of the term to refer to *outer* space—defined as something like "the dimensions of height, depth, and width within which all things exist and move" (source: http://www.oxforddictionaries.com/definition/english/space). Although we cite a specific dictionary definition here, others are similarly circular, using words like "extent," "extension," "area," "depth," "boundless," or "dimensions," all of which require the concept of space for their interpretation. Similarly, "spatial" is typically defined by an expression like "of or relating to space" (source: *Webster's Third New International Dictionary of the English Language*, 1986). Montello and Raubal (2012, p. 249) proposed to define spatiality as the "property of reality that reflects the fact that everything is not at one location," which is only slightly tongue-in-cheek and may be a little less circular than many other definitions.

Fully appreciating how difficult it is to generate a clear and non-circular definition of space and spatial, we nonetheless feel it is worthwhile and important to try. Among other reasons, having a clear understanding of what constitutes space and spatiality is necessary for delimiting what the focus and purpose of spatial education should be (although not sufficient by itself, of course). Indeed, we have frequently encountered broad uses of terms like "spatial thinking" or "spatial learning" that seem appropriate only because they involve some phenomenon that exists in space. Surely we do not want to classify any learning or education involving entities in space or entities with spatial properties as "spatial learning" or "spatial education." After all, all learning, certainly including formal education, occurs in space, involving materials with spatial properties and pedagogical content that concerns entities in space and with spatial properties, at least implicitly (even if it is some form of imaginary or fictional space). Learning literature or arithmetic involves entities that have spatial extent and are accessed in part through their spatiality (e.g., the left to right interpretation of sentences or equations, the orthography of perceiving letters and other symbols, etc.). Instead, we suggest restricting spatial learning and education to learning and education that is primarily, or at least centrally, about spatiality—that focuses on problems that engage spatial properties and their manipulation as a core component, as for example in architectural design, wayfinding, or graph interpretation.

One could explicate (without defining) the meaning of spatiality by listing spatial properties, which would include location, size, distance, direction, shape, connectivity, overlap, dimensionality, hierarchy, and more. Such a list would be large and diverse, although not unlimited. Presumably, it would be useful to organize this list into related terms, such as those reflecting properties of the same dimensionality, of the same discreteness or continuity, at the same scale (relative size), at the same level of geometric sophistication (i.e., topological, projective, affine, or metric geometry), etc. In chapter 11 in this book, Grossner and Janelle take this approach of exploring lists of spatial concepts in different domains as a way to approach the problem of understanding what is the domain of spatial learning and education.

What Are Concepts and Conceptualization?

In addition to the meaning of spatiality, we can consider the question of what concepts are. This too is an abstract question, with a long history of diverse answers (Margolis and Laurence 1999), although it does not beg the question nearly so much as defining spatiality does. We can say in a fairly straightforward way that concepts are the semantic ideas that constitute our understanding of the world and the objects and events that exist in it (whether represented in words or other sign systems). A little more specifically, human beings universally organize the world into categories of entities sharing some form of similarity, and concepts are the intellectual bases for defining the similarity (this is not to say that all humans or human groups necessarily organize in the same way). A little more abstractly, in semiotic terms, concepts are the interpretants that connect sign-vehicles to referents in the world, whether real or hypothetical (MacEachren 1995) or, alternatively, to referents in cognitive models of the world (Kuhn, Raubal, and Gärdenfors 2007). For example, the concept of a dog connects the verbal sign-referent "dog" to the hairy four-legged creature that barks and wags its tail (or to our understanding of that creature).

That said, there have been and still are many trenchant questions about the meaning and nature of concepts, questions that are at the foundation of established research programs in philosophy, psychology, linguistics, and other disciplines. Many have claimed that concepts are to be limited to propositional statements—claims about something that can be phrased in the form of "it is true that ... ," but others do not want to limit concepts in this way, presumably because such a limitation excludes forms of thinking and understanding we want to include, such as sensory imagery or emotionality. Clearly, we have propositional knowledge about spatiality (e.g., "objects that overlap must partially exist in the same space") but we also experience or reason with spatiality in ways we could not or do not express propositionally. More fundamentally, there has long been the question as to whether concepts are properties of the world (abstracta) or only properties of mental representations of the world, or perhaps that they always arise from an interaction of mind and world (i.e., the nature of concepts has been a prominent arena for arguing the mind-body question). Some scholars reject a propositional approach to understanding concepts because they believe no meaning is captured well in terms of the truth of a concept's correspondence to a reality, but instead meaning refers to the way a concept expresses a person's or culture's cognitive model of reality (Kuhn, Raubal, and Gärdenfors 2007). Other questions about the nature of concepts involve whether the form of their mental representation is more like a natural or formal language, a mental image, a spatial model, or something else; how concepts relate to spoken or written natural language, and thus how concepts do or do not vary across cultural groups; whether concepts are necessarily decomposable into primitive or elemental concepts; and more. Additionally, a given spatial concept is seldom used in isolation of other spatial concepts. An example is the application of the overlay concept in geographic information systems, where the concept "overlay" relates to the areal coverage of distinct phenomena in space (soil types, vegetation, hydrology, and so on) to identify regions (another spatial concept) based on overlaps among phenomena as displayed cartographically.

Several different theories of the composition of concepts have been explored in the literature, ranging from the classical idea that concepts delimit a modestly-sized finite set of necessary and sufficient conditions for something to be an example of some type or member of a category (a mostly untenable view, except for formal entities such as those defined in geometry); to the idea of prototype theory that concepts are sets of properties related with varying degrees of similarity to a "good" or "best" schematization of the core meaning of the concept; to the idea of concepts as theories of essential identity that explain why entities have the properties they have or act as they do. Various shades of all these exist, as well as other theoretical approaches altogether (Margolis and Laurence 1999).

We feel comfortable recognizing that concepts and conceptualization are real and are important to learning, knowledge, and reasoning, even if we grant that their ultimate nature is still a matter of debate. We note, however, that much of the academic literature in psychology and philosophy (as in Margolis and Laurence 1999) seems to focus on concepts as categories of entities, such as dogs, chairs, or events, and not on concepts as categories of properties and relations. Properties and relations would be central in spatial education, for example the spatial concepts of distance, location, and scale. We are not certain how straightforward it is to extend models of concepts of entities to models of spatial properties of entities and relations between them. Is it important that concepts as entities are bounded while concepts as properties or relations are relatively unbounded? Perhaps we are really touching here on thinking explicitly with concepts versus thinking with properties and relations, only implicitly with concepts. After all, when one imagines the directions to various places when deciding which way to travel, one is thinking with the spatial property of direction but not *about the concept* of direction.

Thus, we recognize that while concepts and conceptualization are important to human cognition and behavior, they are not all that is relevant to learning and education. Besides conceptual knowledge, humans make decisions and in general interact with the world on the basis of perceptual and motor activity. Much coordinated behavior reflects automatized habits and skilled behavior—I did not employ conceptualization in order to drive home this evening, but I (or my nervous system interacting with the world) definitely processed spatial information in order to pull this off effectively. Thinking, or cognition more broadly, involves low-level and high-level mental processes, implicit and explicit processes (varying in their degree of conscious awareness), and processes that are both bottom-up and top-down. Formal education perhaps most frequently involves relatively high-level tasks, such as those that engage 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. The relative focus of spatial

learning and education on explicit conceptual knowledge vs. other, more implicit forms of spatial knowledge is a substantial question for designers of spatial education and is addressed in several chapters in this book, especially in parts II and IV.

A word about ontologies

The goal of making spatial concepts explicit has been shared over many years by diverse and largely unconnected groups of researchers, and in the next section of this chapter we review some of that work having a particularly pedagogical focus. In the last couple of decades, however, another multi-disciplinary group of researchers, loosely grouped in the field of information theory (including spatial and geographic information), have also attempted to enumerate and in cases organize spatial concepts, under the rubric of *ontology*. Much of this work has been driven not by educational objectives, but by software application requirements.

In the traditional philosophical sense, ontology can be thought of as answering the question "What *is* there?"—i.e., the question of what is the nature of reality, including all types of phenomena and their properties and relations. Those prominently included spatial properties and relations, typically expressed in terms of topology, mereology (the study of parts and wholes), or some type of metric geometry (Smith 1998). Throughout much of the twentieth century, in contrast, various theories within philosophy and the behavioral and cognitive sciences have promoted approaches to comprehending reality and our understanding of reality that see our understanding as reflecting our mental models of reality rather than the reality itself (Kuhn, Raubal, and Gärdenfors 2007).

Such cognitivist approaches to semantics have dovetailed with a desire to understand computational systems and improve their usability for humans. It was recognized that digital representations of reality in computational systems are also essentially models of reality. This led to the burgeoning fields of theoretical and applied formal ontology, which attempt to express ontologies in the formal languages of mathematics, symbolic logic, and the like. Smith (1998) has pointed out that the idea of formal ontology was first proposed by Husserl more than a hundred years ago. A number of researchers within the communities of computational intelligence and information systems, including artificial intelligence (AI), computational linguistics, and database design in various domains (biomedical information, geographic information, etc.), have developed an active interest in formal ontology, including the formal ontology of space and space-time (Guarino 1998; Uschold and Gruninger 1996).

Computational ontologists have recognized the difficulty or even impossibility of capturing all relevant models of the world within a single kind of ontology (Guarino 1998). Very general aspects of reality that should hold across disciplines and topic areas have been proposed to make up a "top-level" (or foundation) ontology. Examples would be space, time, matter, object, and event. Aspects of some reality that would be appropriate for particular domains, or for particular tasks and not others, are subsumed under top-level ontologies and are known as "domain" and "task" ontologies. Subsumed under these are "application" ontologies that apply to particular tasks within the context of particular domains.

The idea that some ontologies and ontology patterns apply very broadly, perhaps universally, and others apply very narrowly or only in specific contexts, presages the question we raise below as to the advisability or viability of developing a domain-general spatial education versus only domain-specific versions. In a way, this book could be considered an ontological investigation into the nature of space and spatiality. We have asked researchers with quite diverse backgrounds and interests, all deeply concerned with spatial concepts and conceptualization, to contribute their own perspectives and priorities in order to inform our collective effort to improve spatial learning and education.

Spatial Concepts, Spatial Thinking, Spatial Learning, and Spatial Education: Why Are They Important?

Spatial concepts are important because they are the basis for much of what we consider to be spatial thinking. Spatial thinking is important because of the critical function it plays in so many tasks—whether specialized or generic, mundane or extraordinary, performed by experts or by novices. Spatial learning in educational and everyday settings is important because it holds the promise of improving spatial thinking, which in turn holds the promise of contributing to a host of desirable outcomes, including generating economic development, making more user-friendly and functional technology, fostering equitable access to employment, and generally helping people realize their potential. To the extent that these claims are valid, there is little doubt that spatial concepts, thinking, and learning are quite important and worthy of our attention as academics, researchers, and educators (National Research Council 2006; Newcombe and Frick 2010).

We can expand on this argument a little. As we have seen, spatial concepts are the structured beliefs people (individually or collectively) hold about the spatial properties of individual and classes of entities, and of the relations among sets of entities and classes of entities. These entities may be real, imagined, or metaphorical. Notwithstanding the caveat that humans frequently act in space in a coordinated manner without invoking conceptual knowledge, conceptual thinking about space and spatiality provides a basis for reasoning about spatiality, playing a central role in numerous human activities and helping to solve numerous problems (Montello and Raubal 2012). It is difficult to overstate the importance and ubiquity of spatial conceptual thinking. People think spatially in order to orient themselves and find their way efficiently to their destinations. Activity planning is part of this, such as when people decide the sequence of their activities based on their beliefs about the relative locations of activity settings. People think spatially as they experience their surroundings, comprehending the meaning of events and objects in part based on the spatial context of the places where the events and objects are encountered; this spatial (or "placial") context becomes a fundamental organizing basis for storing experience in memory (Burgess, Maguire, and O'Keefe 2002) and is of special significance in the humanities where "sense of place" plays a crucial role in establishing meaning to life and human activities (Bodenhamer, Corrigan, and Harris 2010). People think spatially when they choose mechanical tools and manipulate them appropriately, whether in cooking, carpentry, or surgery. People think spatially when they design efficient, functional, or aesthetic relationships between physical entities and environmental settings, whether designing buildings to take advantage of sun directions or *chi* flow, or just packing luggage into a car's trunk so it all fits efficiently without crushing anything. People think spatially when they interpret maps and other geographic information displays, graphs, paintings, and other semiotic entities that express information literally or metaphorically via spatial properties of the symbols and their relations. People also think spatially when they interpret spatiality described in written or spoken natural language, and when they transmit spatiality themselves in verbal descriptions. Such verbal spatiality is not limited to explicit spatial instructions, such as how to put together a toy or find a restaurant—it is replete in narrative fiction and is a key to understanding and enjoying many novels, short stories, and poems.

In sum, we have offered a case for the importance of spatial concepts in the worlds of science and art, and in the planning and organization of human landscapes and human activities. However, if there is a case for embedding explicit opportunities for spatial learning within formal education, then it is also critical that we address the intellectual and institutional contexts of education, drawing on grounded research about spatial concept understanding and its uses across disciplines and in practical applications.

Spatial Education

We believe the emerging development of explicit spatial education should be informed by the research on spatial thinking, learning, and reasoning that has been ongoing for several decades. Behavioral and cognitive scientists have conducted research on human conceptualizations of space for many decades, primarily in the fields of psychology (Newcombe and Huttenlocher 2000), linguistics (Bloom, Peterson, Nadel, and Garrett 1996), and anthropology (Sheets-Johnstone 1990). Spatial researchers in disciplines like geography, geology, and architecture have also shared an interest in understanding and improving how people learn and use spatial concepts to think about spatial problems in their respective domains. More recently, computer and information scientists have become interested in how their databases and computer systems instantiate models of reality, including its spatiality, and how they can design such databases and systems to be compatible with human understanding. In essence, the book we introduce in this chapter is based on the premise that spatial thinking should become an explicit focus of education, promoting it from a subject of incidental and sporadic treatment in uncoordinated disciplinary lessons into a coherent and fundamental push coordinated across disciplines. To put it another way, we endorse Montello's (2008) proposal to add a fourth R to the three educational R's (Reading, 'Riting, and 'Rithmetic): *Räumlichkeit*, the German word for "spatiality." (There is no English word for "space" or "spatial" that begins with an R, and, after English, German may be the most common language of research relevant to research on spatial learning and education.) In advancing this fourth R, we examine briefly its foundations in cognitive and behavioral sciences and in geography and geographic information systems (GIS) education, elaborate on its importance to STEM (science, technology, engineering, and mathematics) learning, and consider its potential as a catalyst for transdisciplinary and collaborative problem solving.

Roots in Psychometrics and Differential Psychology

One of the earliest scholarly efforts to develop spatial education came from psychologists interested in measuring spatial thinking ability (or abilities) and how they differed across individual people. This research started in the

nineteenth century and was especially prominent during the early to mid twentieth century (Eliot 1987; Fruchter 1954; Lohman 1996). Measuring spatial abilities was part of the earliest traditions of *psychometrics*, the subdiscipline of psychology that attempts to measure mental responses that do not correspond in a direct way to any objectively measurable stimulus or property of a person or of the world. General aptitude tests such as the SAT and the GRE include spatial thinking items, although these items are typically aggregated with nonspatial logical and mathematical items when used to make admissions decisions. This psychometric work had the basic-science goal of understanding human mental abilities and the practical goal of selecting people for particular tasks or professions. If an activity requires spatial thinking for its successful completion, then people who think better spatially should be more likely to succeed at it. These scholarly pursuits continue today; tests of spatial thinking are sometimes used, for example, to select from applicants to dental or medical schools (Hegarty, Keehner, Cohen, Montello, and Lippa 2007).

Of course, researchers are quite interested in *explaining* patterns of individual and group differences, not just describing them (McGee 1979). Efforts to measure spatial abilities focus first on treating each individual person as potentially different from other individuals, but scholars (and laypeople) often want to organize and interpret these variations in terms of groups of individuals, most commonly groups based on sex or age (Newcombe and Huttenlocher 2000; Voyer, Voyer, and Bryden 1995), but also those based on professional experience, scholastic major, language, or other aggregating factors. Presumably, identifying group patterns suggests something about the genesis of the variations, but this causal link is quite ambiguous to make, largely because variables such as sex, age, and culture cannot be experimentally manipulated. An excellent discussion of these issues is found in appendix C of the report by the National Research Council's Committee on Support for Thinking Spatially (2006). One common misunderstanding in this regard is the notion that just because some trait is genetically determined, it is necessarily immutable, and that because some trait is modifiable, it must be caused by experiences after birth (or conception) rather than by genetics. Neither of these complementary claims are true. Everyone accepts that body weight is substantially genetically determined at the same time they accept that body weight is also quite modifiable (for those of us with will power, anyway).

Although the validity of using measures of spatial abilities to select personnel would hold to some degree no matter how stable these differences were, it would be more valid to do so if the differences were relatively unmodifiable by training or other experiences. In contrast, if the performance of spatial tasks is not particularly stable and can be substantially modified by explicit training or other experiences, the traditional notion of abilities as stable traits becomes weakened. Of course, if the performance of spatial tasks is readily modifiable, it would be critically important to know that and to know how best to modify them, how long-lasting such modifications would be, and so on. There is an emerging body of research showing that some forms of spatial abilities are trainable, at least to some extent (Lohman and Nichols 1990; Newcombe and Frick 2010), but these are ongoing questions that are actively being researched. For example, the field of medical education continues debating the degree to which the abilities involved in, for example, learning anatomy or performing surgery are modifiable (Hegarty, Keehner, Cohen, Montello, and Lippa 2007).

Over the course of more than a hundred years, psychometric researchers developed and published more than a hundred tests to measure one or another component of spatial thinking. Performance on these spatial intelligence tests were typically developed and interpreted by factor analyzing their patterns of scores; the resulting summary factors have been described by terms such as "spatial visualization" or "spatial orientation." Evidence of distinct components or factors of spatial abilities has long made it clear that we should not conceive of spatial thought as a unitary, monolithic ability. But even this long-standing insight from psychometrics may undersell the multifarious nature of spatial thought (Hegarty and Waller 2005). The components of spatial thinking derived from the psychometric tradition are almost entirely based on "pictorial" tests—two-dimensional, abstract spatial problems presented on pieces of paper or computer screens. But spatial thinking, as we have seen, is much more than this, involving a rich variety of tasks and situation contexts at different spatial scales, dimensionalities, and levels of geometric sophistication. Increasingly, researchers are recognizing limits to the generality of current forms of psychometric spatial tests.

Roots in Geography and Geographic Information Science

A second effort to develop spatial education has come from researchers and teachers interested in educating students about geography, particularly when conceived of as primarily a "spatial" science. Although this is not the only way to think of geography, the spatial tradition in geography has ancient origins, displayed prominently in the cartographic achievements of Claudius Ptolemy (circa 100–178 AD). Later, geo-spatial concepts were

at the core of what Bernhardus Verenius described as "general geography" in his 1650 publication of Geographia Generalis—a volume that was republished several times with updates by notable editors, including one by Isaac Newton in 1681 for teaching geography at Cambridge University; these edited versions of Varenius' work were standard texts in the leading early colonial colleges of America for more than 100 years (Warntz 1989). This spatial tradition was revived in geography's quantitative revolution in the 1950s, and became the focus of research and teaching programs structured around such themes as theoretical geography (Bunge 1962), general spatial systems theory (Coffey 1981), spatial analysis, GIS, and geographic information science (GIScience) (Goodchild 1992).

A specific focus on spatial reasoning about geographic problems emerged gradually but simultaneously with mid-twentieth-century developments in spatial approaches to geography, typically through attempts to distill a finite set of basic or fundamental spatial concepts relevant to geographic education. Nystuen (1968) discussed the idea of understanding geographic analysis in terms of "fundamental spatial concepts." Golledge (1992) further developed the idea of basic spatial concepts, specifically offering them as a rational basis for the design of geographic education curricula. Plumert (1993) explored the implications for geographic education of spatial knowledge development in children. Among the others who have explored an explicit link between spatial concepts and educational development are Gersmehl and Gersmehl (2006) and Golledge, Marsh, and Battersby (2008).

Golledge, Marsh, and Battersby (2008) proposed that spatial concepts could be arranged into five levels defined in terms of the abstractness and complexity of their relationship to a small set of "Level I" primitive spatial concepts, proposed here to include identity (not itself spatial but thematic), location, magnitude, and space-time (the idea of dynamic spatial phenomena). Building on the Level I Primitives, according to these authors, are Level II Simple concepts (e.g., direction, distance), Level III Difficult concepts (e.g., center, growth), Level IV Complicated concepts (e.g., connectivity, scale), and Level V Complex concepts (e.g., central place, projection). The authors empirically investigated the lowest three levels of their taxonomy by asking grade-school children to perform various tests designed to assess their spatial comprehension. For instance, one test required students to generate spatial terms corresponding to concepts depicted pictorially.

Linked to this push from geographic education has been the notion that GIS technology would be an especially effective way to teach spatial concepts and foster spatial reasoning skills, at all levels of formal education from kindergarten through a bachelor's degree. This notion has ranged from the idea that simply using a generic GIS will stimulate spatial thinking to the idea that GIS can be specially designed to support the effective teaching of spatial concepts and reasoning (Lee and Bednarz 2009; National Research Council 2006). Several scholars have advocated, and continue to advocate, for the incorporation of GIS technologies into the classroom at all grade levels. In fact, a handful of courses have been developed around understanding and using GIS as the basis for spatial thinking curricula (Sinton 2009; Spatial Literacy in Teaching, http://www.le.ac.uk/gg/splint/). It is interesting to note that using GIS to stimulate and improve spatial thinking is somewhat converse to one of the original insights of GIScience that we should understand how humans think spatially (and otherwise) so we can improve GIS technologies (Mark and Frank 1991; Montello 2009).

However, some scholars have cast doubt on the advisability of using GIS as the primary tool to teach spatial thinking. For examples, see the position papers of participating researchers and educators in the 2012 Specialist Meeting on "Spatial Thinking Across the College Curriculum" at http://www.spatial.ucsb.edu/events/STATCC/participants.php. Various concerns arise here, including the fact that not all spatiality is geographic and not all geography is spatial (Ishikawa 2013). Perhaps of more concern is that spatial technologies as they exist now work mostly by replacing spatial thinking, rather than enhancing it. In many cases, for instance, technology turns a thinking problem into a perception problem—one enters a command and then reads the answer off the screen. Consider, for example, how GPS vehicle navigation has displaced the use of maps and the reasoning process involved in navigation between locations. Recognizing this and other problems with basing spatial education on GIS technology (hardware and maintenance costs, need for teacher training), some voices promoting GIS for spatial education recommend it play a supporting role only: "Taken alone, GIS is not the answer to the problem of teaching spatial thinking in American schools; however, it can play a significant role in an answer." (National Research Council 2006, p. 8)

The attempt to incorporate GIS technology into spatial education is certainly going to continue. We believe the best bet for the success of this effort is to design systems with spatial education as their goal, not simply shoehorning generic systems into this purpose. This echoes Marsh, Golledge, and Battersby's (2007) proposal to develop a "Minimal GIS" with grade-appropriate pedagogy as its driving inspiration. That is, instead of trying to build systems that will most efficiently solve geospatial problems, appealing to other kinds of bottom lines, we need to build systems designed first and foremost to stimulate mental activity and learning about space and place.

Roots in Science Literacy and STEM Education

A third, more recent effort to develop explicit spatial education has come from a push to improve training in natural science and engineering fields in the United States. In the early 2000s, the National Science Foundation coined the acronym to highlight the need for better educational outcomes in those fields and provide material support for research activities that would ostensibly contribute to that goal. The advent of the acronym manifests a growing urgent concern about science literacy (Laugksch 2000) and American competitiveness in the increasingly global landscape driving so much of the world economy (Gonzalez and Kuenzi 2012). The American Association for the Advancement of Science, a primary initiator of this discussion, has promoted science literacy as "what all students should know and be able to do in science, mathematics, and technology by the time they graduate from high school" (AAAS 1993, p. xi) and specified its conceptual content in a progression of increasing complexity in application through grade levels K–12. At this writing, the STEM learning focus continues to grow, evidenced by two major learning standards initiatives for schools in the United States, Common Core State Standards Initiative (CCSS; http://www.corestandards.org/) and Next Generation Science Standards (NGSS; http://www.nextgenscience.org/).

Improving spatial learning and developing spatial education has emerged as a major focus of the push to improve STEM education and increase the supply of U.S. trained scientists and engineers. This is based on the proposed importance of spatial thinking in STEM fields and the idea that improving spatial skills will improve training in STEM fields and increase access of STEM professions to underrepresented groups, including women and some ethnic minorities. *Learning to Think Spatially* (National Research Council 2006) argued this case forcefully. (See also Uttal and Cohen 2012.) The report recommended that a program of scientific research be supported to better understand the link between spatial thinking and STEM and to experimentally evaluate instructional practices in the spatial domain. The same year this report was published, the National Science Foundation funded a program exactly along those lines, the Spatial Intelligence Learning Center, headquartered at Temple University; it has recently been refunded through 2016. The stated mission of the center is "to develop the new science of spatial learning and to use this knowledge to transform STEM educational practice."

As Gonzalez and Kuenzi (2012) observe, STEM originally (and still, for many people and institutions) referred to biophysical sciences only (as well as math and engineering). However, for the National Science Foundation, STEM now includes behavioral and social sciences. Presumably, spatial thinking is not equally involved in the reasoning and problem solving of all these scientific disciplines. A more dramatic development that has garnered interest from NSF and from industry is the transition from STEM to STEAM, the A standing for Art; the intent here is to highlight the potential for innovation by bringing together the cultures of art and science. Art programs focus on creativity in a broad range of disciplines that are spatial in their conceptions and execution. A partial list includes apparel design and textile art, architecture, ceramics, digital media (film, animation, video), furniture design, glass, graphic design, history of art and visual culture, illustration, industrial design, interior architecture, jewelry and metalsmithing, landscape architecture, painting, photography, printmaking, and sculpture. It is possible that a broad integration of STEM with art will help to foster an implicit spatial frame of mind for learning, potentially encouraging creativity that could benefit society.

Multi-Disciplinary, Inter-Disciplinary, and Trans-Disciplinary Visions

Besides the disciplinary-specific motivations we have just reviewed (differential psychology, geography/GIScience, STEM/STEAM education), one can identify other contributions to the emergence of explicit spatial education. Child and developmental psychologists have long studied the development of spatial thinking skills, strategies, and mental representations in children (Newcombe and Huttenlocher 2000). Scholars within several other disciplines have shown interest in the idea that educating students specifically in spatial thinking will improve learning of their subject. Prominent examples include geology and other earth sciences (Kastens and Ishikawa 2006), chemistry (Wu and Shah 2004), physics (Pallrand and Seeber 1984), astronomy (Taylor, Barker, and Jones 2003), mathematics (Battista 2007; Bishop 1980), medicine and dentistry (Hegarty, Keehner, Cohen, Montello, and Lippa 2007), and architecture (Roberts 2007). But education in spatial thinking is not relevant only to academic or scientific pursuits. It applies to many non-academic pursuits, such as carpentry, sewing, auto mechanics, interior decorating, taxi driving, athletics, and more (Gauvain 1993; National Research Council 2006). Whether academic, technical, or otherwise, spatial thinking in these domains is relevant to thinking about phenomena that make up the domain of interest itself (such as the spatial arrangement of molecules or furniture) as well as thinking *with* symbolic representations that encode spatial properties of the phenomena, such as maps, graphs, photographs, verbal descriptions, or physical models (Card, MacKinlay, and Schneiderman 1999; Hegarty and Just 1993; MacEachren 1995).

Spatial education is clearly a very multidisciplinary endeavor. We hope with this book to push it toward *inter*disciplinarity, implying the emergence of at least some common vocabulary and methods concerning spatial teaching and research that is shared across disciplines. Sometimes the term *trans*disciplinary is used to imply studies that don't merely combine disciplines but transcend them; a truly general spatial education that we can imagine would not be contained within any single discipline or even any single set of related disciplines. We see the potential audience for discussions of spatial learning and education as spanning many scientific and educational research communities concerned with spatial and spatio-temporal learning and education. It should also interest scholars in philosophy and in many engineering and design professions, including art, and dance.

Overview of the Book

This book presents a sampling of some of the major approaches to understanding the concepts, principles, and methods people with different backgrounds, disciplines, and purposes use to think, learn, and reason about spatial aspects of problems and situations, specifically exploring the implications of these approaches for educating people about space and spatiality. We hope the book contributes to advancing ongoing efforts to design and evaluate curricula to foster spatial thinking in the sciences, humanities, and other fields. It is intended to highlight broad aspects of our basic understanding of spatial thinking, learning, and reasoning, and to help bring together diverse disciplines and research communities, summarizing some of the work to date, exploring connections, and pointing toward future progress and potential for integration.

We have been guided in developing this book by several overarching questions. Can spatial ability and reasoning skills be improved by instructional practice, and presuming that it can, how? Are there spatial concepts, principles, and reasoning tasks that are general across all fields? If there are, what are they and how can they be characterized? What are useful or appropriate ways to organize these concepts and reasoning processes? Promising candidates include spatial scale (from nano to cosmic), the mental processes involved (mental rotation, pattern recognition, etc.), the context of activity (i.e., cognition in space, about space, with space), and the knowledge domain involved (e.g., the natural sciences, engineering, social sciences, art, mathematics, history). Can we identify and explicate the correct or most useful spatial conceptual distinctions within and across disciplines? Is a unified conceptual system (ontology) for spatial thinking and reasoning a feasible and worthwhile goal? If so, for what purposes? Or will it ultimately prove more productive to focus on discipline-specific approaches to spatial education? Of course, this book does not definitively answer these central questions, but we do believe it helps bring them into focus.

There are sixteen chapters, some of them focused particularly on education and others on spatial learning more generally. The chapters are organized in five parts, each of which we introduce with a short discussion.

Chapters 1–3 make up part I of the book. These chapters look at some of the philosophically broadest and most fundamental issues surrounding research on spatial learning and education.

In this introductory chapter, we present the topic of the book and its motivation. We consider broad issues concerning the meaning of space and spatiality, of concepts and conceptualization, and of spatial thinking in the context of learning and education. This chapter also lists some of the fundamental questions facing those who wish to construct explicit spatial curricula.

In chapter 2, Christian Freksa and Holger Schultheis of the Cognitive Systems Group at the University of Bremen argue that generic or universal approaches to spatial learning and education will fall short, because specific problem domains are so determinative of how people think about and reason with spatiality. Freksa and Schultheis present three approaches to spatial problem solving that differentially employ explicit or implicit mental representations of spatial properties, based on (1) knowledge in the world, or acting in space, (2) knowledge in the head, or solving spatial problems mentally, and (3) knowledge distributed between the world, the body, and the mind, or embodied and situated cognition. Clearly, many effective and efficient approaches to spatial problem solving exploit the specific spatial and temporal structures of a problem situation without explicitly representing them mentally. Spatial learning and education should not be constructed only around explicit, conceptual knowledge of space and spatiality, but recognize the role of spatial structure in the mind, in the body, and in objects and environmental surrounds. As a case in point, people often "think" spatially by directly interacting with and manipulating their physical spatial environment rather than by interacting with mental representations or external symbolic representations, such as verbal descriptions, graphs, or maps.

In chapter 3, John Bateman of the Department of Applied Linguistics at the University of Bremen and Sander Lestrade of the Department of Language Typology at the University of Amsterdam discuss the common role of spatial thinking of various types in almost all human activities. In many situations, however, spatial beliefs must be shared among individuals, and this most often occurs through natural language (English, German, etc.). Understanding how spatial language expresses meaning—expresses a spatial ontology—is very complex and involves a host of thorny issues concerning the mind and body, the mind and language, cross-linguistic similarities and differences, and more. In particular, there is no straightforward translation between spatial language and spatial meaning. This chapter highlights some of the subtle complexities of expressing and interpreting spatiality in language, a common format by which people learn spatial information, especially in formal educational settings.

The chapters in part II look at the role of visualization, both external (graphs, diagrams, maps) and internal (visual imagery and other mental spatial representations), in spatial learning and education.

Chapter 4 is authored by Mary Hegarty of the Department of Psychological & Brain Sciences at the University of California at Santa Barbara, Mike Stieff of the Department of Chemistry at the University of Illinois at Chicago, and Bonnie Dixon of the Department of Chemistry and Biochemistry at the University of Maryland. External and internal spatial representations are clearly critical to spatial learning and education, and this chapter contributes to our understanding of how the two types of spatial representations operate singly and in combination. The authors provide a novel framework for classifying strategies people use to solve spatial problems that distinguishes whether the strategy (1) recruits spatial versus nonspatial information, (2) relies primarily on internal versus external representations, and (3) involves modification of representations. As an example, the framework is applied to the domain of spatial problem solving in organic chemistry.

In chapter 5, Scott R. Hinze of the Department of Psychology and School of Education and Social Policy at Northwestern University, Vickie M. Williamson of the Department of Chemistry at Texas A&M University, Mary Jane Shultz of the Department of Chemistry at Tufts University, Ghislain Deslongchamps of the Department of Chemistry at the University of New Brunswick, Kenneth C. Williamson of the Department of Construction Science at Texas A&M University, and David N. Rapp of the Department of Psychology at Northwestern University also discuss the role of external spatial representations (often called visualizations) in education, specifically science and engineering education. Such visualizations have long been used in science education, in part because of their power to depict spatial relationships, including those showing parts of reality that are too small or large, too slow or fast, or otherwise exist in reality in an obstructed, unobservable manner. However, an important question is how and how well these visualizations work for people of varying spatial abilities. The authors summarize literature on this question and present empirical evidence from their own work.

In chapter 6, Ranxiao Frances Wang of the Department of Psychology at the University of Illinois at Urbana-Champaign considers the fascinating possibility that humans can directly intuit spaces of four dimensions, and that the classic idea (as espoused by Kant and others) that human spatial apprehension is limited to three dimensions is not true. Phenomenological reports of four-dimensional spatial imagination have long been met with skepticism, and it is very difficult to evaluate such claims conclusively from systematic empirical exploration. But Wang attempts to do so and claims that such "extra-dimensional" spatial thought can be demonstrated. If so, we may need to expand our understanding of fundamental limits on spatial learning and education.

The chapters in part III expand on the theme set forth in chapter 2 by Freksa and Schultheis by providing perspectives from behavioral science on embodied spatial learning and education. Embodied cognition recognizes that humans usually interact "corporeally" with spatial properties of reality, and that this corporeal interaction is essential to how people understand space and learn about it.

David Waller of the Department of Psychology at Miami University lays out many of these conceptual issues in chapter 7. Waller advocates for understanding spatial learning and thinking not as mental spatial representations of the environment employing symbolic and arbitrary codes but as the mental structures and processes involved in perceiving and acting in the world. This is a novel conceptualization of spatial learning compared to a traditional cognitivist perspective—it does away with symbolic mental representation and makes it easier to explain a continuity between the

thinking of humans and other animals. Waller applies his embodied approach to an analysis of spatial reference systems in thought.

In chapter 8, Evie Malaia of the Department of Linguistics at the University of Texas at Arlington and Ronnie B. Wilbur of the Department of Speech, Hearing, and Language Sciences at Purdue University remind us that spatial language is not only spoken or written, but exists for many people in a "manual" form, wherein static and dynamic spatial patterns of the hands and arms convey rich content about spatial properties and relations in the world. According to Malaia and Wilbur, sign language has profound effects on how its users perceive and conceive of spatiality in the world. An interesting implication for general spatial education is that some of the positive intellectual effects of using sign language can even be promoted in students without auditory impairments, when sign language is taught as a second language.

In chapter 9, Kinnari Atit and Thomas F. Shipley of the Department of Psychology and the Spatial Intelligence and Learning Center at Temple University and Basil Tikoff of the Department of Geology at the University of Wisconsin at Madison look at embodied spatial learning and education. Focusing not on sign language (a fully grammatically developed natural language) but on more common manual gestures used to convey spatial relations, they consider the notoriously difficult spatial problem of teaching students about the spatial properties of geological strata. They extend a previous framework for understanding spatial discourse and apply it to understanding gestures in spatial education in the geosciences.

In chapter 10, Alycia M. Hund of the Department of Psychology at Illinois State University discusses spatial strategies used during wayfinding, which consists of the orientation and decision-making components of coordinated travel through the environment. The strategy choice Hund specifically examines concerns thinking of the environment from a route perspective or a survey perspective. The route perspective is like a mental tour of the environment from a first-person, terrain-level perspective. It is conceptualized as embodied travel. In contrast, the survey perspective is like a disembodied, third-person view from above the environment. The distinction between route and survey strategies has emerged as one of the fundamental contrasts between different strategies for thinking spatially about the environment; it differentiates individuals, females and males, and approaches to problems phrased in different ways. The author advocates the value of promoting flexibility and adaptability in spatial strategy use as a way to improve spatial performance in a variety of problem-solving contexts.

Part IV consists of chapters 11–14, which examine the development and explicit instruction of spatial thinking and reasoning within and without the contexts of various disciplines.

In chapter 11, Diana S. Sinton, Executive Director of the University Consortium for Geographic Information Science, lays out many of the basic considerations for those who would design explicit spatial curricula. Although initially motivated within the context of geography and GIS, Sinton's efforts have gone beyond that to designing, implementing, and evaluating generic spatial curricula. She provides a working definition of spatial thinking as the ability to visualize and interpret location, position, distance, direction, movement, change, and relationships over space. The chapter concludes with specific advice for designing effective spatial curricula.

Chapter 12, by Karl Grossner of Stanford University Libraries and Donald G. Janelle of the Center for Spatial Studies at the University of California at Santa Barbara, is a wide-ranging investigation of spatial concepts and principles as they are used in many different disciplinary contexts, then organized into several categories in a speculative undergraduate course outline. The authors present empirical methods for identifying spatiality in the academic writing of various disciplines. The richness and heterogeneity of spatial concepts is nowhere on display more in this book than in this chapter.

In chapter 13, Thora Tenbrink of the Department of Linguistics and English Language at Bangor University, Christoph Hölscher of the Program in Cognitive Science at the Swiss Federal Institute of Technology, Dido Tsigaridi of the School of Design at Harvard University, and Ruth Conroy Dalton of the Department of Building Usability and Visualization at Northumbria University examine communicating about spatial and other properties of built spaces within another very spatial discipline: architecture. Interestingly, spatial conceptualization is different for the architect, the client, and a building's users. The variable spatial worldviews should be incorporated into spatial education, in this case, architectural education.

In chapter 14, Roger M. Downs of the Department of Geography at Pennsylvania State University uses a clever task to get at people's geo-spatial thinking in a way that avoids the pitfall of asking people to explicitly state their thoughts. The task, first suggested several decades ago by the geographic theorist William Bunge, provides people with part of a simple map-like representation of a landscape (including natural and cultural features) and asks them to predict what the neighboring landscape will look like. Downs analyzes possible responses to this task in terms of various levels of geo-spatial expertise, demonstrating the specialized nature that spatial learning can take with professionals who have spent many years thinking in particular spatial problem domains.

Part V contains two complementary epilogue chapters, one by Michael F. Goodchild, Emeritus Professor of Geography and Past Director of the Center for Spatial Studies at the University of California at Santa Barbara and one by Nora S. Newcombe of the Department of Psychology and the Spatial Intelligence and Learning Center at Temple University. These chapters nicely address fundamental issues concerning prospects and problems for developing effective spatial education and the role that spatial technologies play in spatial learning and education now and in the future.

Although no volume of modest size could capture more than a small fraction of the potential work and authors that might appropriately contribute to a book on this topic, we believe the chapters represent an interesting and important collection of multi-disciplinary scholarly thought on spatial conceptualization with implications for learning and education.

References

AAAS. 1993. *Benchmarks for Science Literacy*. ERIC Clearinghouse.

Battista, M. T. 2007. The development of geometric and spatial thinking. In *Second Handbook of Research on Mathematics Teaching and Learning*, ed. F. K. Lester Jr. Information Age.

Bishop, A. J. 1980. Spatial abilities and mathematics education—A review. *Educational Studies in Mathematics* 11: 257–269.

Bloom, P., Peterson, M. A., Nadel, L., and Garrett, M. F., eds. 1996. *Language and Space*. MIT Press.

Bodenhamer, D. J., Corrigan, J., and Harris, T. M., eds. 2010. *The Spatial Humanities: GIS and the Future of Humanities Scholarship*. Indiana University Press.

Bunge, W. 1962. *Theoretical Geography*. Department of Geography, Royal University of Lund

Burgess, N., Maguire, E. A., and O'Keefe, J. 2002. The human hippocampus and spatial and episodic memory. *Neuron* 35: 625–641.

Card, S. K., MacKinlay, J. D., and Schneiderman, B. 1999. *Readings in Information Visualization: Using Vision to Think*. Morgan Kaufmann.

Coffey, W. J. 1981. *Geography: Towards a General Spatial Systems Approach*. Methuen.

Dear, M., Ketchum, J., Luria, S., and Richardson, D., eds. 2011. *GeoHumanities: Art, History, Text at the Edge of Place*. Routledge.

Eliot, J. 1987. *Models of Psychological Space: Psychometric, Developmental, and Experimental Approaches*. Springer.

Fruchter, B. 1954. Measurement of spatial abilities: History and background. *Educational and Psychological Measurement* 14: 387–395.

Gauvain, M. 1993. The development of spatial thinking in everyday activity. *Developmental Review* 13: 92–121.

Gersmehl, P. J., and Gersmehl, C. A. 2006. Wanted: A concise list of neurologically defensible and assessable spatial-thinking skills. *Research in Geographic Education* 8: 5–38.

Golledge, R. G. 1992. Do people understand spatial concepts: The case of first-order primitives. In *Theories and Methods of Spatio-Temporal Reasoning in Geographic Space*, ed. A. U. Frank, I. Campari, and U. Formentini. Springer.

Golledge, R. G., Marsh, M., and Battersby, S. 2008. A conceptual framework for facilitating geospatial thinking. *Annals of the Association of American Geographers* 98: 285–308.

Gonzalez, H. B., and Kuenzi, J. J. 2012. Science, technology, engineering, and mathematics (STEM) education: A primer. Congressional Research Service, August 1.

Goodchild, M. F. 1992. Geographical information science. *International Journal of Geographical Information Systems* 6: 31–45.

Goodchild, M. F., and Janelle, D. G., eds. 2010. Toward critical spatial thinking in the social sciences and humanities. *GeoJournal* 75: 3–13.

Guarino, N. 1998. Formal ontology and information systems. In *Formal Ontology in Information Systems*, ed. N. Guarino. IOS Press.

Hegarty, M., and Just, M. A. 1993. Constructing mental models of machines from text and diagrams. *Journal of Memory and Language* 32: 717–742.

Hegarty, M., Keehner, M., Cohen, C. A., Montello, D. R., and Lippa, Y. 2007. The role of spatial cognition in medicine: Applications for selecting and training professionals. In *Applied Spatial Cognition: From Research to Cognitive Technology*, ed. G. L. Allen. Erlbaum.

Hegarty, M., and Waller, D. 2005. Individual differences in spatial abilities. In *The Cambridge Handbook of Visuospatial Thinking*, eds. P. Shah and A. Miyake. Cambridge University Press.

Ishikawa, T. 2013. Geospatial thinking and spatial ability: An empirical examination of knowledge and reasoning in geographical science. *Professional Geographer* 65: 636–646.

Kastens, K. A., and Ishikawa, T. 2006. Spatial thinking in the geosciences and cognitive sciences: A cross-disciplinary look at the intersection of the two fields. In *Earth and Mind: How Geologists Think and Learn about the Earth*, ed. C. A. Manduca and D. Mogk. Geological Society of America.

Kuhn, W., Raubal, M., and Gärdenfors, P. 2007. Editorial: Cognitive semantics and spatio-temporal ontologies [Special issue]. *Spatial Cognition and Computation* 7: 3–12.

Laugksch, R. C. 2000. Scientific literacy: A conceptual overview. *Science Education* 84: 71–94.

Lee, J., and Bednarz, R. 2009. Effect of GIS learning on spatial thinking. *Journal of Geography in Higher Education* 33: 183–198.

Liben, L. S. 2006. Education for spatial thinking. In *Handbook of Child Psychology*, sixth edition, volume 4: *Child Psychology in Practice*, ed. K. A. Renninger and I. E. Sigel. Wiley.

Lohman, D. F. 1996. Spatial ability and g. In *Human Abilities: Their Nature and Measurement*, ed. I. Dennis and P. Tapsfield. Erlbaum.

Lohman, D. F., and Nichols, P. D. 1990. Training spatial abilities: Effects of practice on rotation and synthesis tasks. *Learning and Individual Differences* 2: 67–93.

MacEachren, A. M. 1995. *How Maps Work: Representation, Visualization, and Design*. Guilford.

Margolis, E., and Laurence, S., eds. 1999. *Concepts: Core Readings*. MIT Press.

Mark, D. M., and Frank, A. U., eds. 1991. *Cognitive and Linguistic Aspects of Geographic Space*. Kluwer.

Marsh, M., Golledge, R., and Battersby, S. E. 2007. Geospatial concept understanding and recognition in G6–college students: A preliminary argument for minimal GIS. *Annals of the Association of American Geographers* 97: 696–712.

McGee, M. 1979. Human spatial abilities: Psychometric studies and environmental, genetic, hormonal, and neurological influences. *Psychological Bulletin* 86: 889–918.

Montello, D. R. 2008. Review of *Learning to Think Spatially*. *Journal of Environmental Psychology* 28: 104–106.

Montello, D. R. 2009. Cognitive research in GIScience: Recent achievements and future prospects. *Geography Compass* 3; 1824–1840.

Montello, D. R., and Raubal, M. 2012. Functions and applications of spatial cognition. In *Handbook of Spatial Cognition*, ed. D. Waller and L. Nadel. American Psychological Association.

National Research Council. 2006. *Learning to Think Spatially*. National Academies Press.

Newcombe, N. S., and Frick, A. 2010. Early education for spatial intelligence: Why, what, and how. *Mind, Brain, and Education* 4: 102–111.

Newcombe, N. S., and Huttenlocher, J. 2000. *Making Space: The Development of spatial representation and reasoning*. MIT Press.

Nystuen, J. D. 1968. Identification of some fundamental spatial concepts. In *Spatial Analysis: A Reader in Statistical Geography*, ed. B. J. L. Berry and D. F. Marble. Prentice-Hall.

Pallrand, G. J., and Seeber, F. 1984. Spatial ability and achievement in introductory physics. *Journal of Research in Science Teaching* 21: 507–516.

Plumert, J. M. 1993. The development of children's spatial knowledge: Implications for geographic education. *Cartographic Perspectives* 16: 9–18.

Roberts, A. S. 2007. Predictors of future performance in architectural design education. *Educational Psychology* 27: 447–463.

Scholten, H. J., van de Velde, R., and van Manen, N., eds. 2009. *Geospatial Technology and the Role of Location in Science*. Springer.

Sheets-Johnstone, M. 1990. *The Roots of Thinking*. Temple University Press.

Sinton, D. S. 2009. Roles for GIS within higher education. *Journal of Geography in Higher Education* 33: S7–S16.

Sklar, L. 1974. *Space, Time, and Spacetime*. University of California Press.

Smith, B. 1998. Basic concepts of formal ontology. In *Formal Ontology in Information Systems*, ed. N. Guarino. IOS Press.

Taylor, I., Barker, M., and Jones, A. 2003. Promoting mental model building in astronomy education. *International Journal of Science Education* 25: 1205–1225.

Uschold, M., and Gruninger, M. 1996. Ontologies: Principles, methods and applications. *Knowledge Engineering Review* 11: 93–136.

Uttal, D. H., and Cohen, C. A. 2012. Spatial thinking and STEM education: When, why and how. In *Psychology of Learning and Motivation*, volume 57, ed. B. H. Ross. Academic Press.

van Fraassen, B. C. 1985. *An Introduction to the Philosophy of Time and Space*, second edition. Columbia University Press.

Voyer, D., Voyer, S., and Bryden, M. P. 1995. Magnitude of sex differences in spatial abilities: A meta-analysis and consideration of critical variables. *Psychological Bulletin* 117: 250–270.

Warf, B., and Arias, S. 2009. *The Spatial Turn: Interdisciplinary Perspectives*. Routledge.

Warntz, W. 1989. Newton, the Newtonians, and the Geographia Generalis Varenii. *Annals of the Association of American Geographers* 79: 165–191.

Wu, H. K., and Shah, P. 2004. Exploring visuospatial thinking in chemistry learning. *Science Education* 88: 465–492.