Chapter 3
Spatial Thinking in Education: Concepts, Development, and Assessment

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Abstract Spatial thinking has always been a fundamental cognitive skill for competency in geography. However, interest in it has increased in recent years as technological advances have driven political and societal changes producing a renewed awareness of its importance. This is especially true in the context of geospatial technologies (GST). The growth, expansion, and power of GST demands a citizenry with well-developed spatial thinking skills. But research exploring spatial thinking in an educational context is scant.

This chapter explores the current position of spatial thinking in education. First, we describe existing research in spatial thinking. We focus on advances in technology which have led, in part, to the increased interest in the topic. The roles of spatial thinking and GST in curricula are explored. Promising methods for assessing students' spatial thinking are reviewed in order to provide guidance for curriculum decision-making. The chapter concludes with a summary of the current state of spatial thinking in education and with recommendations for further research.

Keywords Spatial thinking • Geography education • Geospatial technologies

3.1 Spatial Thinking in Education: Concepts, Development, and Trends

Spatial thinking has always been a fundamental cognitive skill in geography. Space is a key organizing concept for our discipline. Moreover, geographers use spatial thinking supported by spatial representations such as maps to: pose geographic questions; collect, organize, and analyze geographic information; and explain and

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communicate geographic patterns and processes—practices critical to the development of twenty-first century competencies (Bednarz et al. 2013). Technological factors including the explosion of location-based geospatial technologies (GST), such as geographic information systems (GIS), and political and social forces have combined to drive a renewed awareness of, and interest in, spatial thinking. These developments have also contributed to "the spatial turn" in geography (Goodchild and Janelle 2010).

This chapter explores the current position of spatial thinking in education. First, we briefly review definitions of spatial thinking and four conceptualizations of how spatial thinking develops in individuals. Second we describe the political, social, and technological factors driving interest and research in spatial thinking in education. In the third section we examine efforts to assess spatial thinking that may provide evidence to guide curriculum decisions regarding the teaching and learning of spatial thinking. The chapter concludes with recommendations for further research.

3.2 Definition of Spatial Thinking

Spatial thinking can be defined as a constructive combination of cognitive skills comprised of knowing concepts of space, using tools of representation, and applying processes of reasoning (NRC 2006, p. 12). Spatial thinking allows people to use space to model the world (real and theoretical), structure problems, find answers, and express and communicate solutions. The inclusion of concepts of space makes spatial thinking unique from other types of thinking (NRC 2006). Concepts of space are declarative forms of knowledge, the building blocks for spatial thinking. Location, dimensionality, continuity, pattern, spatial association, network, and proximity are examples of spatial concepts that have been explicitly recognized by researchers (Gersmehl and Gersmehl 2007; Golledge 2002; Janelle and Goodchild 2009). Tools of representation such as maps, graphs, sketches, diagrams, images, and models enable and support spatial thinking. They are used in a variety of modes (mental images, visual media, tactile, auditory, and kinesthetic forms) to identify, describe, explain, and communicate information about objects and their associated spatial characteristics (NRC 2006).

Spatial thinking often necessitates complex reasoning (Jo and Bednarz 2009). Reasoning is the capacity of individuals to think, make sense of the world, and understand. Processes of reasoning are crucial for learning as individuals obtain, change, or justify practices, institutions and beliefs (Kompridis 2010). Processes of reasoning include low levels of thinking, such as recognizing, defining, and listing, and higher levels of thinking, such as evaluating, synthesizing, and generalizing (Jo and Bednarz 2009).

3.3 Conceptualizations of Spatial Thinking

Understanding spatial thinking in terms of human development and learning is a necessary precursor to discussions of current trends, and interest, in teaching spatial thinking. One of the most important debates informing spatial thinking in education concerns the extent to which spatial thinking is, in some sense, innate. Many researchers have attempted to conceptualize the development of spatial thinking (Allen 2003; Kuipers 1978; MacEachren 1992; Montello 1998; Newcombe and Learmonth 2005). These theories can be grouped into four broad categories: nativist, Piagetian, Vygotskyan, and interactionist (Kim et al. 2012). Nativists argue that children are born with a biologically determined level of spatial thinking, and, even though spatial thinking may develop with age and experience, biology pre-determines ability. Contrary to the nativist approach Piaget argued that "infants are born without knowledge of space, and without a conception of permanent objects which occupy and structure that space" (Newcombe and Huttenlocher 2003). Piagetians propose a sequential progression of understanding from topological space to projective and Euclidean space (Piaget and Inhelder 1948). The egocentric-to-allocentric shift predicted by the Piaget approach has inspired a large volume of research related to spatial thinking in education (Downs and Liben 2001; Golledge et al. 1993; Shelton and McNamara 2004; Thommen et al. 2010). Both the nativist and the Piagetian conceptualizations of spatial thinking minimize or ignore the social and cultural influences on humans' development of spatial thinking, for example, the role played by cultural tools such as language or maps. Those who view spatial thinking with a Vygotskyan (or sociocultural) conceptualization emphasize these social and cultural influences on individual intellectual development and encourage the examination of cultural tools and environments that affect human development (Gauvain 2008). The interactionist conceptualization of spatial thinking asserts that components of each of the previously discussed approaches are valid; newborn children likely arrive with a set of biologically determined innate spatial abilities as nativists argue, children and novices show predictable developmental transitions as a Piagetian approach would argue, and the influence of life experienced through culture and cultural tools is clearly evidenced in the variance of spatial thinking observed across individuals and cultures (Newcombe 2000). The interactionist approach argues for the influence of both nature and nurture on the cognitive development of spatial thinking.

Educational approaches for fostering spatial thinking typically utilize an interactionist approach because it recognizes that individuals have different starting points for spatial thinking, but spatial skills can be improved through training and scaffolding. An interactionist approach provides teachers and policy makers with the opportunity to consider a wide range of educational strategies. Even though students bring different spatial thinking approaches and preferences to the classroom, tools of representation paired with quality instruction can enhance and develop multiple strategies for spatial thinking.

3.4 Interest in Teaching Spatial Thinking

Geospatial technologies (GST), defined as technologies that facilitate visualization, measurement, mapping, wayfinding, or spatial analysis of features both concrete and conceptual on Earth's surface and subsurface, have become ubiquitous, and now location matters more than ever. Paper maps have been replaced by smartphones with digital maps, navigation systems, and global positioning units (GPS). Most vehicles are also equipped with these technologies. We report our location frequently through social media. Web-based mapping and analysis software give even a novice user access to a wide variety maps and to constantly growing functionality to display and analyze spatial data (see for example GIS Cloud at http://www.giscloud.com/). The widespread availability of GSTs, however, does not ensure that users can employ these technologies competently. For example, an over-reliance on navigation systems has resulted in people losing their way. In remote locations, such as California's Death Valley, the lack of "competent application" of GST can be a matter of life and death (Clark 2011).

To apply spatial thinking effectively, individuals require a spatial awareness or spatial literacy that does not necessarily develop as a consequence of using GST. If, as Ellul (1964) argues, technology is a sociological phenomenon, GST has generated social change, which in turn has driven political change. These changes have created a society awash in spatial data yet lacking the cognitive skills and the spatial "habit of mind" to use that data to solve problems, make decisions, or affect policy. As a result, society has begun to recognize the importance of a population who are competent spatial thinkers. Interest in teaching and learning spatial thinking is increasing, creating a challenge and an opportunity for geography education to lead in establishing a spatial thinking culture.

3.4.1 Technological Advances Driving Sociocultural and Political Change

The spatial revolution started thousands of years ago with maps. A map can be considered technology, or tool, that facilitates problem solving and decision making. However, prior to the invention of the printing press, it was impossible to distribute maps widely. Following the printing revolution, maps became more commonly available contributing to a cultural shift from a "manuscript culture" to a "print culture" (Finkelstein and McCleery 2002).

A second technological advancement occurred during World War I when aerial photography was combined with cartography to create and revise maps. This integration of technologies led to a cultural shift in how the surface of the earth was perceived—from a "view from below" to a "view from above." It demonstrated that geographic phenomena, both physical and social, are embedded in patterned spatial relationships that cannot be seen from ground level and led to the emergence of a new way of conceptualizing socio-spatial relationships. This new conceptualization resulted from the advancement of technology. Once introduced, it was manifested in society and policy through instructional programs such as France's use of "air-mindedness" to promote nationalism in schools and to understand long-term urban spatial stratification from aerial photographs of French cities (Haffner 2013).

The current turn in the spatial revolution is driven by the pervasive nature of GST. Maps that were printed, static, and clumsy are now digital, dynamic, interactive, and convenient. Maps and the spatial information derived from them are available everywhere, all of the time. Maps can be modified, created, and displayed by novices. This has led to a rethinking of maps and new understandings about their roles in spatial practices (Kitchin and Dodge 2007). A map can be created almost instantaneously by anyone to organize and display spatial information or phenomena (Edelson 2012). These developments have encouraged research about teaching and learning spatial thinking in order that individuals acquire the necessary cognitive skills to productively participate in a spatial culture inundated with GST.

Any educational emphasis on spatial thinking will be influenced by the support of government agencies and policy makers. Typically educational innovations are implemented only after societal evaluation, a process influenced by the endorsements of legislatures and policy makers. As governments standardize data formats and as public resources are dedicated to spatial learning and educational practice, educators have an increasing responsibility to include spatial thinking in their instruction.

3.4.2 Educational Applications

Driven by the social and political changes resulting from advances in GST, a *proto-spatial thinking culture* exists today. This culture is characterized by the widespread availability of GST but the limited spatial thinking ability of most people to use these technologies effectively. Spatial thinking is perhaps the most important factor that determines competency in spatially dependent disciplines such as geography and other STEM disciplines (Newcombe 2010; Wu and Shah 2004; Pallrand and Seeber 1984; Hsi et al. 1997; Kali and Orion 1996; Shea et al. 2001). Numerous studies have found a significant correlation between spatial thinking and success in spatially dependent tasks, performance in undergraduate science courses, and persistence in science careers (Anderson and Leinhardt 2002; Black 2005; Kali and Orion 1996; Keehner et al. 2006; Pallrand and Seeber 1984).

Researchers indicate that spatial thinking ability increases students' likelihood of pursuing a degree or career in STEM (Kheener et al. 2006; Shea et al. 2001) and that spatial thinking is malleable—it can be improved with training (Newcombe 2010). Many educational interventions for improving spatial thinking have been reported: (a) attention to the acquisition and use of spatial vocabulary (Bednarz and Bednarz 2008; Gentner 2007); (b) facilitating mental images through the use of gestures (Newcombe 2010); (c) use of analogies to identify similarities between un-like objects or phenomena (Loewenstein and Gentner 2005); (d) use of student sketches to represent conceptual models (McNeal et al. 2008); and (e) use of representations such as maps and GST (Uttal 2000; Anderson and Leinhardt 2002).

Classroom-based research has found that the use of GST, specifically GIS, improves knowledge of spatial concepts and the ability to think spatially. Lee and Bednarz (2009) found a positive relationship between the number of GST courses (e.g., GIS or Computer Cartography) completed by undergraduate students and their scores on a spatial-skills test. Even students who completed only one GIS course showed significant gains in spatial skills. Working with elementary students, Shin (2006) used qualitative analysis to demonstrate a positive relationship between the use of GST and students' learning and cognitive strategies.

3.4.3 Spatial Thinking in the Curriculum

This section asks, what is the interaction between acquiring content knowledge and spatial thinking? Three types of spatial thinking exist, depending on the context in which the spatial thinking takes place (NRC 2006). Walking to school or playing a team sport such as football—actions that are performed in space—require spatial thinking in a real-world context, referred to as the "geography of life spaces." The second type of spatial thinking, thinking about space, is typically employed when individuals use spatial thinking to learn how the world works. It is termed "the geography of physical spaces." The third type of spatial thinking, thinking with space, is abstract yet powerful. Educators often encourage students to "map" their understanding of relationships and concepts. We make lists, doodles, graphic organizers, diagrams, and graphs to explore data. Spatializing non-spatial data or using space as an organizing framework is an effective cognitive strategy. This third context results in a "geography of intellectual spaces."

The opportunity for students to learn "in space" varies greatly. Informal education such as scouting or sports can engage learners' abilities in wayfinding and in understanding location in space. Many other opportunities to learn about space exist, particularly in science courses such as geography, but the essence of spatial thinking, thinking about space, is rare in curricula we have examined. We argue for a concerted effort to introduce and institutionalize this perspective, and essential element of geography, into curriculum worldwide.

Previous research indicates that a spatial-thinking curricula must consider five issues. First is the importance of the individual learner. Spatial skills develop uniquely for different individuals. Sex, experience, age, culture, and education all play a role in the acquisition of key spatial thinking competencies. Second, context matters. Research confirms that expertise develops in specific contexts or disciplines and that transfer from one area to another is not automatic (National Research Council 1999). Thus, curricula should be developed across disciplines with spatial thinking in mind. Third, scale matters. Differences in large-scale and small-scale spatial thinking exist similar to differences in thinking in, about, and with space (Hegarty et al. 2006). Fourth, task analysis and alignment matter. It is essential that curricula include activities aligned to the three types of spatial thinking (*in* space, *about* space, or *with* space) in order to clarify the kinds of experiences that promote spatial skills and to understand the roles that individual differences play in spatial thinking. Finally, teaching matters. The findings indicate that spatial thinking can, and should, be learned by everyone (NRC 2006; Bednarz and Bednarz 2008). Thus, teacher preparation and professional development are key to improving spatial thinking (Jo and Bednarz 2014).

3.5 Assessment

In addition to questions concerning the conceptualization of spatial thinking and strategies to improve it, another issue involves the assessment of spatial thinking. Before researchers can detect changes, they must be able to measure an individual's spatial thinking ability. Spatial ability, a concept generally thought to be more specific than spatial thinking, has been the subject of research by practitioners from a wide range of disciplines.

In general, researchers agree that at least two spatial abilities exist, spatial visualization and spatial orientation. Tests are available to measure visualization—the ability to mentally represent and operate on visual stimuli—and orientation—the ability to picture spatially arrayed elements from different perspectives (e.g., Goldstein et al. 1990; Kail et al. 1979; Newcombe and Dubas 1992). These assessment instruments, however, leave many geographers and earth scientists dissatisfied because of their small scale and the restricted set of abilities they measure (Self et al. 1992; Golledge 1993; Montello et al. 1999; Lee and Bednarz 2009). Geographers and their colleagues have expressed a desire for an instrument that would assess what Golledge and Stimson (1997, p. 158) defined as spatial relations: "…abilities to recognize spatial distributions and spatial patterns, to connect locations, to associate and correlate spatially distributed phenomena, to comprehend and use spatial hierarchies, to regionalize, to orientate to real-world frames of reference, to imagine maps from verbal descriptions, to sketch map, to compare maps, and to overlay and dissolve maps."

The lack of test instruments for these abilities or skills leads researchers to create several "spatial analysis tests" (Kerski 2000; Marsh et al. 2007; Huynh and Sharpe 2013; Jo and Bednarz 2009). Many of these assessments were developed for relatively specific purposes, often based on specific curriculum elements (Huynh and Sharpe 2013) or to evaluate students' prerequisite knowledge (Jo and Bednarz 2009). Other tests were not examined for their validity and reliability. One recently developed assessment, the Spatial Thinking Abilities Test (STAT), was created using a recommended, five-step, test-development procedure (Lee and Bednarz 2012). Questions were created based on hypothesized spatial thinking components identified in the literature (Golledge et al. 2008; Gersmehl and Gersmehl 2006).

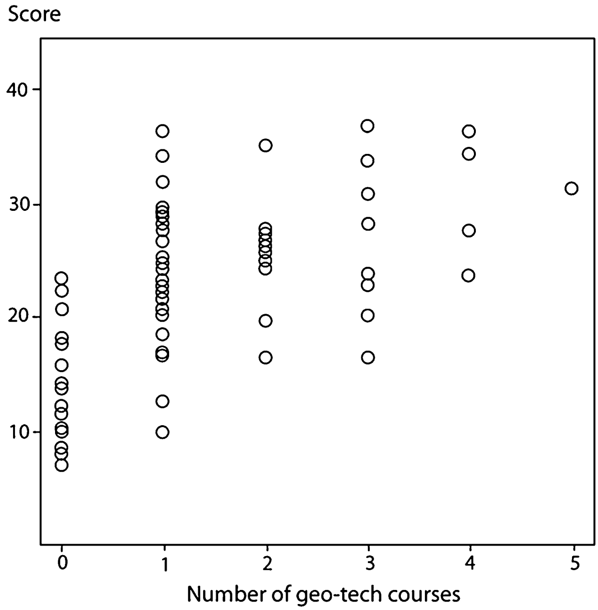

Fig. 3.1 Number of GIS courses completed by the subjects and their average scores in the spatial-skills test

The Spatial Thinking Abilities Test has been administered widely to a diverse set of subjects in many countries. It was used to measure subjects' mastery of the content and skills contained in the Association of American Geographers' *Teachers' Guide to Modern Geography*, a program to improve the ability of geography teachers to introduce spatial thinking into the classroom. STAT was also administered to undergraduate students to determine the effect of completing a geo-spatial technology course (i.e., GIS, cartography, or remote sensing) on their spatial thinking skills (Lee and Bednarz 2009). The pilot test revealed a positive correlation of 0.58 between the number of GIS or geo-technology courses completed and students' STAT scores (Fig. 3.1).

Following the pilot, 80 students enrolled in Computer Cartography, Introduction to GIS, and Economic Geography in a department of geography at a large public university completed both pre- and post-tests, before they began and after their semester-long courses (Table 3.1).

For additional applications of the STAT and a call for additional research on spatial thinking assessment, see Lee and Bednarz (2012) and Kim and Bednarz (2013).

Table 3.1 A comparison of pre- and post-test scores by group

		Pre-test		Post-test		
	N	Mean	S.D.	Mean	S.D.	Score difference
Control	35	11.171	5.046	11.71	4.773	0.542
Cartography only	18	12.972	5.829	14.11	4.629	1.138
GIS only	17	12.500	5.172	14.97	4.777	2.470*
Cartography and GIS						
Sequentially	7	17.571*	3.194	19.00	2.449	1.428
Concurrently	3	12.333	5.276	13.83	4.963	1.200

Students' average scores (Table 3.1 and Fig. 3.2) indicated that GIS students scored significantly higher on the post-test, although it should be noted that the number of students in each group is not large
*$p < 0.05$

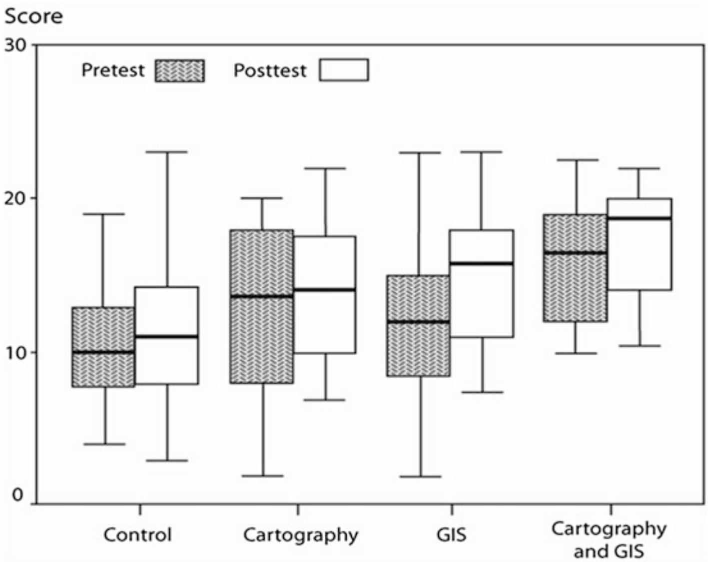

Fig. 3.2 A comparison of pre- and post-test scores by group

3.6 Conclusion

The chapter concludes with recommendations for further research. Technological changes, the spatial turn, and consequent social and political forces are producing a demand for a citizenry with the knowledge, skills, and practices of spatial thinking. The implications for geography educators are immense. People will need and want to know how to acquire, interpret, and contribute geographic information. The task increasingly is to prepare technologically enabled, spatially literate individuals. It will be a challenge (but also a considerable opportunity) to plan and to provide a level of understanding of spatial concepts and reasoning processes through geography (Bednarz et al. 2013). First, we may need to examine educational standards and their role in instruction in spatial thinking. In the United States, the National Geography Standards have been revised to embrace spatial thinking as a central mission. The term *spatial thinking* was inserted into the first Standard, *How to use maps and other geographic representations, GSTs, and spatial thinking to understand and communicate information*. Enhanced expectations regarding the use of GST to produce and interpret maps and solve spatial problems were included across all 18 Standards. The impact of this educational change remains to be researched.

A second area that remains unclear in a research sense is the relationships between spatial thinking and geography education, particularly at the intersection with GST. To focus and build capacity in geography education related to spatial thinking, four research questions are suggested to frame an agenda:

1. How does spatial thinking develop across individuals, settings, and time?
2. How does spatial thinking develop across the different realms of geography?
3. What supports or promotes the development of spatial thinking?
4. What is necessary to support the effective and broad implementation of the knowledge, skills, and practices of spatial thinking?

Finally, we suggest researchers carry out lines of research with select attributes, including the use of shared tasks, measurements and assessments such as the STAT to accumulate data on the core ideas, practices, and characteristics of spatial thinking.

References

Allen, G. L. (2003). Functional families of spatial abilities: Poor relations and rich prospects. *International Journal of Testing, 3*(3), 251–262.

Anderson, K. C., & Leinhardt, G. (2002). Maps as representations: Expert novice comparison of projection understanding. *Cognition and Instruction, 20*(3), 283–321.

Bednarz, R. S., & Bednarz, S. W. (2008). The importance of spatial thinking in an uncertain world. In D. Z. Sui (Ed.), *Geospatial technologies and homeland security* (pp. 315–330). Dordrecht: Springer Science.

Bednarz, S. W., Heffron, S., & Huynh, N. T. (2013). *A road map for 21st century geography education: Geography education research. Research document*. Geography Education Research Committee of the Road Map for 21st Century Geography Education Project. National Geographic Society. http://education.nationalgeographic.com/education/programs/road-map-project/?ar_a=1. Accessed 6 Oct 2014.

Black, A. A. (2005). Spatial ability and earth science conceptual understanding. *Journal of Geoscience Education, 53*(4), 402–414.

Clark, K. (2011). The GPS: A fatally misleading travel companion. *National Public Radio*. http://www.npr.org/2011/07/26/137646147/the-gps-a-fatally-misleading-travel-companion. Accessed 6 Oct 2014.

Downs, R. M., & Liben, L. S. (2001). The development of expertise in geography: A cognitive-developmental approach to geographic education. *Annals of the Association of American Geographers, 81*(2), 304–327.

Edelson, D. C. (2012). Unlocking the educational potential of citizen science. Resource document. *ArcNews*. http://www.esri.com/news/arcnews/spring12articles/unlocking-the-educational-potential-of-citizen-science.html. Accessed 6 Oct 2014.

Ellul, J. (1964). *The technological society*. New York: Vintage Books.

Finkelstein, A., & McCleery, D. (2002). *The book history reader*. London: Routledge.

Gauvain, M. (2008). Vygotsky's sociocultural theory. In M. M. Haith & J. B. Benson (Eds.), *Encyclopedia of infant and early childhood development* (pp. 404–413). Oxford: Elsevier.

Gentner, D. (2007). Spatial cognition in apes and humans. *Trends in Cognitive Sciences, 11*(5), 192–194.

Gersmehl, P. J., & Gersmehl, C. A. (2006). Wanted: A concise list of neurologically defensible and assessable spatial thinking skills. *Research in Geographic Education, 8*, 6–37.

Gersmehl, P. J., & Gersmehl, C. A. (2007). Spatial thinking by young children: Neurologic evidence for early development and "educability". *Journal of Geography, 106*(5), 181–191.

Goldstein, D., Haldane, D., & Mitchell, C. (1990). Sex differences in visual–spatial ability: The role of performance factors. *Memory & Cognition, 18*(5), 546–550.

Golledge, R. G. (1993). Geographical perspectives on spatial cognition. In T. Gärling & R. G. Golledge (Eds.), *Behavior and environment: Psychological and geographical approaches* (pp. 16–46). Amsterdam: Elsevier Science.

Golledge, R. G. (2002). The nature of geographic knowledge. *Annals of the Association of American Geographers, 92*(1), 1–14.

Golledge, R., & Stimson, R. (1997). *Spatial behavior: A geographic perspective*. New York: The Guilford Press.

Golledge, R. G., Dougherty, V., & Bell, S. (1993). *Survey versus route-based wayfinding in unfamiliar environments*. University of California Transportation Center, University of California Berkeley. http://uctc.net/research/papers/214.pdf. Accessed 6 Oct 2014.

Golledge, R. G., Marsh, M., & Battersby, S. (2008). Matching geospatial concepts with geographic educational needs. *Geographical Research, 46*(1), 85–98.

Goodchild, M. F., & Janelle, D. G. (2010). Toward critical spatial thinking in the social sciences and humanities. *GeoJournal, 75*(1), 3–13.

Haffner, J. (2013). *The view from above: The science of social space*. Boston: MIT Press.

Hegarty, M., Montello, D. R., Richardson, A. E., Ishikawa, T., & Lovelace, K. (2006). Spatial abilities at different scales: Individual differences in aptitude-test performance and spatial-layout learning. *Intelligence, 34*, 151–176.

Hsi, S., Linn, M., & Bell, J. (1997). The role of spatial reasoning in engineering and the design of spatial instruction. *Journal of Engineering Education, 86*(2), 151–158.

Huynh, N., & Sharpe, B. (2013). An assessment instrument to measure geospatial thinking expertise. *Journal of Geography, 112*(1), 3–17.

Janelle, D. G., & Goodchild, M. F. (2009). Location across disciplines: Reflections on the CSISS experience. In D. Z. Sui (Ed.), *Geospatial technology and the role of location in science* (pp. 15–29). Dordrecht: Springer Science.

Jo, I., & Bednarz, S. W. (2009). Evaluating geography textbook questions from a spatial perspective: Using concepts of space, tools of representation, and cognitive processes to evaluate spatiality. *Journal of Geography, 108*, 4–13.

Jo, I., & Bednarz, S. W. (2014). Developing pre-service teachers' pedagogical content knowledge for teaching spatial thinking through geography. *Journal of Geography in Higher Education, 38*(2), 301–313.

Kail, R., Carter, R., & Pellegrino, J. (1979). The locus of sex differences in spatial ability. *Perception & Psychophysics, 26*(3), 182–186.

Kali, Y., & Orion, N. (1996). Spatial abilities of high-school students in the perception of geologic structures. *Journal of Research in Science Teaching, 33*, 369–391.

Keehner, M., Lipa, Y., Montello, D., Tendick, F., & Hegarty, M. (2006). Learning a spatial skill for surgery: How the contributions of ability change with practice. *Applied Cognitive Psychology, 20*, 487–503.

Kerski, J. J. (2000). *The implementation and effectiveness of GIS technology and methods in secondary education*. Unpublished doctoral dissertation, University of Colorado, Boulder.

Kim, M., & Bednarz, R. S. (2013). Development of critical spatial thinking through GIS learning. *Journal of Geography in Higher Education, 37*(3), 350–366.

Kim, M., Bednarz, R. S., & Kim, J. (2012). The ability of young children to use spatial representations. *International Research in Geographical and Environmental Education, 21*(3), 261–277.

Kitchin, R., & Dodge, M. (2007). Rethinking maps. *Progress in Human Geography, 31*(3), 1–14.

Kompridis, N. (2010). So we need something else for reason to mean. *International Journal of Philosophical Studies, 8*(3), 271–295.

Kuipers, B. (1978). Modeling spatial knowledge. *Cognitive Science, 2*, 129–153.

Lee, J., & Bednarz, R. S. (2009). Effect of GIS learning on spatial thinking. *Journal of Geography in Higher Education, 33*(2), 183–198.

Lee, J., & Bednarz, R. S. (2012). Components of spatial thinking: Evidence from a spatial thinking ability test. *Journal of Geography, 111*(1), 15–26.

Loewenstein, J., & Gentner, D. (2005). Relational language and the development of relational mapping. *Cognitive Psychology, 50*, 315–353.

MacEachren, A. M. (1992). Application of environmental learning to spatial knowledge acquisition from maps. *Annals of the Association of American Geographers, 82*(2), 245–274.

Marsh, M., Golledge, R., & Battersby, S. (2007). Geospatial concept understanding and recognition in G6–college students: A preliminary argument for minimal GIS. *Annals of the Association of American Geographers, 97*(4), 696–712.

McNeal, K. S., Miller, H. R., & Herbert, B. E. (2008). The effect of using inquiry and multiple representations on introductory geology students' conceptual model development of coastal eutrophication. *Journal of Geoscience Education, 56*(3), 201–211.

Montello, D. R. (1998). A new framework for understanding the acquisition of spatial knowledge in large-scale environments. In M. J. Egenhofer & R. G. Golledge (Eds.), *Spatial and temporal reasoning in geographic information systems* (pp. 143–154). New York: Oxford University Press. http://www.geog.ucsb.edu/~montello/pubs/microgenesis.pdf. Accessed 6 Oct 2014.

Montello, D. R., Lovelace, L. L., Golledge, R. G., & Self, C. M. (1999). Sex-related differences and similarities in geographic and environmental spatial abilities. *Annals of the Association of American Geographers, 89*, 515–534.

National Research Council. (1999). *How people learn: Brain, mind, experience, and school*. Washington, DC: The National Academies Press.

National Research Council. (2006). *Learning to think spatially: GIS as a support system in the K-12 curriculum*. Washington, DC: The National Academies Press.

Newcombe, N. S. (2000). So, at last we can begin. *Developmental Science, 3*(3), 276–278.

Newcombe, N. S. (2010). Picture this: Increasing math and science learning by improving spatial thinking. *American Educator, 34*(2), 29–43.

Newcombe, N. S., & Dubas, J. S. (1992). A longitudinal study of predictors of spatial ability in adolescent females. *Child Development, 63*, 37–46.

Newcombe, N. S., & Huttenlocher, J. (2003). *Making space: The development of spatial representation and reasoning*. Cambridge, MA: MIT Press.

Newcombe, N. S., & Learmonth, A. E. (2005). Development of spatial competence. In P. Shah & A. Miyake (Eds.), *The Cambridge handbook of visuospatial thinking* (pp. 213–256). New York: Cambridge University Press.

Pallrand, G. J., & Seeber, F. (1984). Spatial abilities and achievement in introductory physics. *Journal of Research in Science Teaching, 21*(5), 507–516.

Piaget, J., & Inhelder, B. (1948). *A child's conception of space*. English edition: Langdon, F. J. & Lunzer, J. L. (1967) New York: Norton.

Self, C. M., Gopal, S., Golledge, R. G., & Fenstermaker, S. (1992). Gender-related differences in spatial abilities. *Progress in Human Geography, 16*, 315–342.

Shea, D. L., Lubinksi, D., & Benbow, C. P. (2001). Importance of assessing spatial ability in intellectually talented young adolescents: A 20-year longitudinal study. *Journal of Educational Psychology, 93*(3), 604–614.

Shelton, A. L., & McNamara, T. P. (2004). Orientation and perspective dependence in route and survey learning. *Journal of Experimental Psychology, 30*(1), 158–170.

Shin, E. (2006). Using geographic information systems (GIS) to improve fourth graders' geographic content knowledge and map skills. *Journal of Geography, 105*(3), 109–120.

Thommen, E., Avelar, S., Sapin, V. Z., Perrenoud, S., & Malatesta, D. (2010). Mapping the journey from home to school: A study on children's representation of space. *International Research in Geographical and Environmental Education, 19*(3), 191–205.

Uttal, D. H. (2000). Seeing the big picture: Map use and development of spatial cognition. *Developmental Science, 3*(3), 247–264.

Wu, H., & Shaw, P. (2004). Exploring visuospatial thinking in chemistry learning. *Science Education, 88*, 465–492.