The Geological Society of America
Special Paper 486
2012

Finding the spatial in order to teach it

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Geoscience and geography educators are joined by cognitive psychologists at the forefront of recent efforts to make the instruction of spatial concepts, spatial skills, and spatial reasoning methods a more explicit part of K–12 and college curricula. In this volume, Liben and Titus closely examined a realistic scenario of a day's fieldwork in the professional practice of a geologist. Jo and Bednarz (2009) analyzed questions from four geography textbooks and developed a "taxonomy of spatial thinking" to help inform curriculum design. Another project, under way at this writing, involves encoding questions from a large number of New York State Earth Science Regents exams in terms of spatial concepts, cognitive processes, and representation types (Kastens and Passow, 20 April 2011, personal commun.); project results will guide the design of professional development programs for teachers. In each case, investigators are "finding the spatial"—in scientific practice, in teaching materials, and in assessment instruments—so that spatial concepts, principles, and reasoning skills might be more effectively taught. In many respects, this amounts to finding, labeling, and classifying what is in plain sight. Spatiality is a fundamental aspect of the natural world and of human cognition and reasoning, but the notion of fostering spatial intelligence and spatial literacy in a directed way has gained attention only recently (Newcombe, 2006).

It is not surprising that professionals from disciplines intensively studying spatial phenomena at geographic scales would actively pursue these goals. Indeed, the subtitle of the influential National Research Council report (NRC, 2006), *Learning to Think Spatially* is *GIS as a Support System in the K–12 Curriculum*. To their credit, that report's authors considered *all* aspects of spatial thinking, regardless of whether GIS was likely to be an effective support tool in each and every case (it isn't). Spatial concepts, skills, and reasoning are vital in numerous disciplines concerned with phenomena at other scales, from nano to microscopic to astronomical, as well as in day-to-day life. This fact has been duly noted in the NRC report and elsewhere, but intensive efforts to improve spatial literacy in concrete ways, such as those mentioned here, have had a disciplinary focus. As a practical matter, it is necessary to bound studies somehow, and academic disciplines are an obvious choice. Investigators will naturally focus on their areas of expertise, and, ultimately, many specific changes to instructional practice are likely to be subject specific. However, there are also good reasons to aim for generality—at least to investigate whether a conceptual framework for spatial learning that encompasses most or all subject domains is warranted or feasible.

Do physicists, biologists, geoscientists, and geographers think about *scale* in the same way? In any case, how do their conceptions of scale relate to those of engineers, urban designers, or artists? What about all of the other spatial concepts that would seem to be discipline neutral (Table 1). If there are commonalities, as seems likely, how will it benefit us to explicate them? To begin answering such questions, it is helpful to have an integrated conceptual framework encompassing numerous disciplinary perspectives on spatial ability, thinking, reasoning, intelligence, and literacy—terms that are sometimes used interchangeably and could be more rigorously defined.

Liben and Titus have shown that "core competencies" for the geosciences concerning map use, orientation, and "specialized spatial diagrams" rely on both conceptual knowledge and cognitive abilities. Relevant concepts are both generic (scale and orientation) and domain specific (strike and dip). The cognitive abilities involved, including spatial visualization, mental rotation, perspective-taking, and spatial memory, are quite generic.

The competencies that Liben and Titus describe correspond closely with the "elements of spatial thinking" introduced in the NRC (2006) report, a definitional framework comprising concepts of space, tools of representation, and processes of reasoning. A second framework from that report, "component tasks of spatial thinking," clearly elaborates the third element (although not necessarily exhaustively), and these have been joined in Figure 1.

I also make explicit in this merged framework a set of somewhat obvious distinctions between internal (i.e., mental) processes and external tools. As detailed in the *Learning to Think*

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Grossner, K., 2012, Finding the spatial in order to teach it, *in* Kastens, K.A., and Manduca, C.A., eds., Earth and Mind II: A Synthesis of Research on Thinking and Learning in the Geosciences: Geological Society of America Special Paper 486, p. 87–89, doi:10.1130/2012.2486(15). For permission to copy, contact editing@geosociety.org.

TABLE 1. SELECTED FUNDAMENTAL SPATIAL CONCEPTS (IN CATEGORIES)

Objects, properties, and parts	Object, size, shape, composition, structure, texture, surface, center
Spatiotemporal context	Space, space-time, location, place, setting, environment
Position	Distance, direction, orientation, grid, coordinates
Spatial dynamics	Form, grow, diminish, merge, split, motion, trajectory, dispersion, diffusion, wave, force, attract, repel
Spatial relations	Adjacency, proximity, centrality, distribution, density
Spatial interaction	Connection, link, bond
Spatial structures	Network, region, neighborhood, landmark, cycle
Spatial transformations	Scaling, rotation, projection, integration, interpolation
Representation	Map, diagram, graph, cognitive map

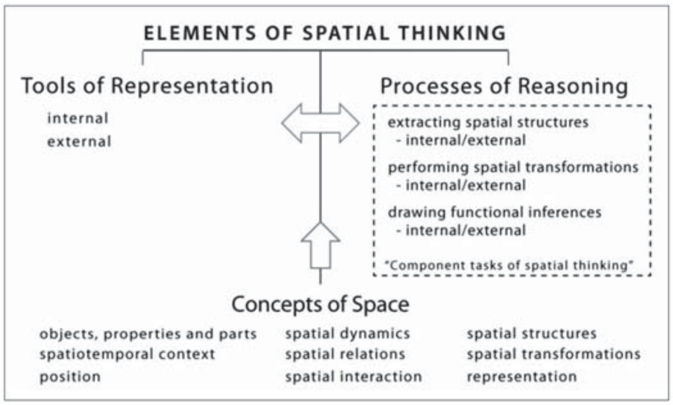

Figure 1. Elements and component reasoning tasks of spatial thinking.

Spatially report and the spatial cognition literature, complex spatial thinking frequently entails complex, iterative interaction between the two. We make both mental maps and physical ones; representations are encoded both in spatial memory and in the symbolic languages committed to paper and hard disks. From our earliest years, we extract spatial structures both consciously and unconsciously, with perception and categorization; later on, we encode our mental models in computer programs in order to analyze and discover both concrete and abstract spatial structures. Spatial transformations to aid reasoning are both internal (e.g., object rotation, cross-section visualization, and alternate perspectives) and external (e.g., overlays for spatial integration, scaling, and dimension reduction). Inferential reasoning processes for generating knowledge can be mental or computational, and variously intuitive, heuristic, or formal.

Liben and Titus provide an interesting example of these relationships in discussing stereographic projections, a sophisticated and flexible representation technique used by many disciplines, the competent application of which requires cognitive ability, representation and reasoning skills, and conceptual knowledge.

The extended framework of Figure 1 outlines schematically a scientific process of (1) observation and measurement; (2) representation, in mental models and imagery, linguistic and mathematical symbols, and graphics; and (3) analysis of these data using both computational and human reasoning, enabling (4) inferential knowledge about the world. Underlying that process, there is a foundation of conceptual knowledge appropriate to the level of each inquiry. To discover and elaborate spatial concept categories, researchers at the University of California–Santa Barbara Center for Spatial Studies have undertaken several efforts aimed at "finding the spatial" in the language of various textual material across a spectrum of disciplines (see, for example, Grossner and Montello, 2009).

In an informal collaborative study with eight "spatial experts" from the fields of geography, geoscience, psychology, mathematics, and math education, we identified spatial concept terms present in the 150 National Science Education Standards (NRC, 1996) for physical, life, and earth and space science subject areas and subjectively rated each standard for its spatiality.[1] We then developed a statistical measure of salience for each tagged term derived from the number of standards in which it appeared, the rated "spatiality level" of those standards, and the agreement between taggers. The results make clear that while many concepts are shared by these scientific domains, there are distinct differences (Fig. 2). One cause for differences is seen in the way highly general terms from the physical sciences are narrowed in other fields. For example, "motion" is differentiated elsewhere as "movement," "transport," "rotation," "circulation," etc. Another, fairly striking result is that some significant spatial concepts are largely absent, including "region," "area," and "pattern." Our subsequent examination of the National Geography Standards (Bednarz et al., 1994) found they are dominant there. Exploration and explanation of such gaps and differences between domains constitute an important spatial ontology research agenda.

The undertaking to "infuse spatial thinking throughout the curriculum" (Newcombe, 2006, p. B20) is both important and achievable, and the interdisciplinary work undertaken for the geoscience and geography domains represents an instructive and invaluable beginning.

Ultimately, experts from many other science, technology, engineering, and mathematics (STEM) fields should collaborate

[1]Work performed as an element of the TeachSpatial project (http://teachspatial.org), supported by National Science Foundation award #1043777.

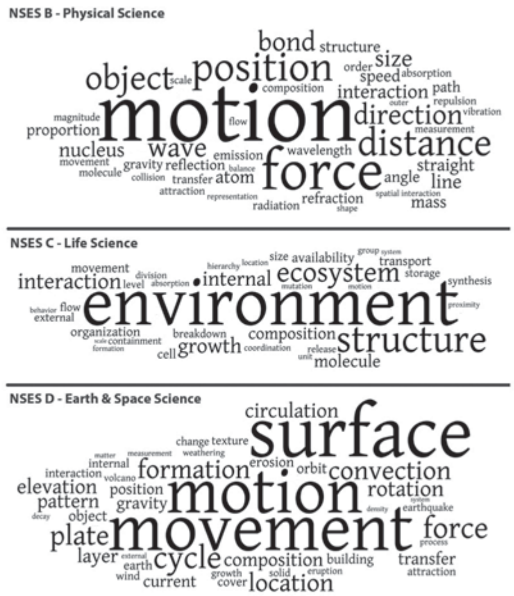

Figure 2. Spatial terms in National Science Education Standards (NRC, 1996); size corresponds to salience.

similarly with cognitive psychologists and educational specialists in defining explicit spatial learning objectives in the context of each discipline considered—a large undertaking indeed. By locating and measuring spatial language in several contexts, and then organizing the underlying concepts, we hope to assist researchers outside of the geosciences and geography in pursuing the kind of intensive analysis undertaken by Liben and Titus and the others mentioned herein.

The further question of whether a set of highly general spatial learning objectives will be useful and achievable presents important research challenges, many of which are now being addressed, for example, by researchers at the Spatial Intelligence and Learning Center (SILC) (http://spatiallearning.org/). It seems intuitively the case that the most primitive spatial concepts, introduced in early childhood, would be highly general. Also, since competency at discipline-specific spatial reasoning tasks relies on core spatial cognitive abilities, efforts to help early learners reach their full potential at these will be crucial.

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Manuscript Accepted by the Society 7 November 2011

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Geological Society of America Special Papers 2012;486; 87-89
doi:10.1130/2012.2486(15)

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