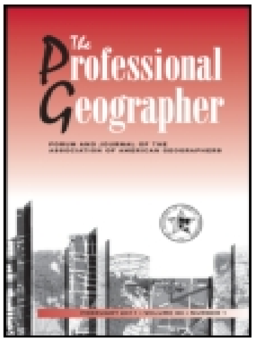

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Synthesized Model of Geospatial Thinking

Amy Lobben
University of Oregon

Megan Lawrence
Cognito

Since the National Research Council (2006) report *Learning to Think Spatially* formalized geospatial thinking, researchers and educators have recognized the importance of investigating and understanding geospatial thinking. Conceptual frameworks have been developed and applied to individual research projects. Although useful in these contexts and potentially extendable to other related inquiries, they also overlap and conflict with one another. Moreover, the separate frameworks are built on different constructs, resulting in a disparate rather than a cohesive theoretical foundation for geospatial thinking. This article synthesizes existing frameworks and generates a model that represents conceptual advances and provides a foundation for research question generation. **Key Words: geospatial thinking, human information processing, model, synthesis.**

自从国家研究委员会 (2006) 的报告”学习以空间的方式思考”将地理空间思考正式化之后, 研究者与教育者认识到探问、并理解地理空间思考的重要性。已有概念架构建立并应用至个别的研究计画中, 这些概念架构儘管在其脉络中有所用处, 并具有延伸至其他相关问题的潜能, 但它们却也部分重叠并相互冲突。再者, 分离的架构各自建立在不同的构想之上, 导致了不同的、而非连贯的地理空间思考的理论基础。本文合成既有的架构, 并创造能够呈现概念前瞻性、提供研究问题生产基础的模型。 **关键词: 地理空间思考, 人类信息处理, 模型, 合成**。

Desde cuando el informe *Learning to Think Spatially* [“Cómo pensar espacialmente”] del National Research Council (2006) formalizó esta forma de analizar el espacio terrestre, investigadores y educadores han reconocido la importancia de investigarla y entenderla. Al respecto, se han desarrollado y aplicado diversos marcos conceptuales en proyectos de investigación individual. Si bien son útiles en estos contextos y potencialmente aplicables en otros estudios relacionados, esas estructuras conceptuales también suelen traslaparse y entrar en conflicto mutuo. Más aún, los marcos individuales son construidos sobre diferentes constructos, dando por resultado algo más discrepante que una fundamentación teórica cohesiva del pensamiento geoespacial. En este artículo se sintetizan los marcos conceptuales existentes y se deriva un modelo que representa los avances conceptuales, planteando un punto de partida para la formulación de preguntas de investigación. **Palabras clave: pensamiento geoespacial, procesamiento de información humana, modelo, síntesis.**

The 2006 National Research Council (NRC) report *Learning to Think Spatially* formalized, popularized, and situated geospatial thinking squarely within geography. Since then, researchers and educators throughout the discipline have recognized the importance of investigating, understanding, and actively teaching geospatial thinking. Geography is not just a natural home for such activities; we are the only discipline in which nearly every construct, theory, and method is spatially grounded. Geographers and geography provide a unique and powerful lens through which to understand geospatial thinking as a newly evolving field. We must not simply play a role in the study of geospatial thinking, but we must push the boundaries. Just as we saw geography lead the empirical and applied development of geographic information science, we should witness the same in the development of geospatial thinking as an interdisciplinary area of study, led by the geographic discipline.

People think about space, make decisions about and within space, and behave in space. Geospatial thinking is a fundamental human geography construct. The importance of the role of geospatial thinking in understanding many scientific ideas is well recognized. More nebulous, however, is an agreed-on definition of what geospatial thinking actually is. Definitions range from broad generalizations—“acquiring knowledge, structuring and solving problems, and expressing the solutions effectively using the properties of space” (Asami and Longley 2012, 975)—to specific, skill-based ideas—“identifying, analyzing, and understanding the location, scale, patterns, and trends of the geographic and temporal relationships among data, phenomena, and issues” (Kerski 2013). Compounding the problem of disparate definitions, neither a standard lexicon nor a standard ontology provide a framework for organizing geospatial thinking constructs and generating hypotheses and research questions. The lack of agreement is not due to empirically based theoretical arguments between scholars. Rather, the difference is a consequence of the relative infancy of geospatial thinking as both a concept and area of research within geography. As a result, geographers are still seeking to identify definitions, ontologies, specific geospatial

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thinking skills, pedagogical applications, and empirical research questions. Throughout this discussion, we talk about the broad geographic concept of geospatial thinking, which, as we and others contend, is composed of dozens of individual geospatial thinking skills. Breaking apart the term *geospatial thinking*, *geospatial* is often used in geographic information systems (GIS) to refer only to positional data, but here this term is expanded to include ideas or concepts and is also narrowed from general spatial to specifically geospatial. *Thinking*, then, is the human brain function or cognitive process that considers and creates meaning around something. As will unfold in the following discussion, the synthesized model considers both terms, geospatial and thinking, in its construction. The fact that we are discussing geospatial means that the individual geospatial thinking skills are inherently geographic constructs, with some more general and some more specific. The inclusion of thinking means that the process of geospatial thinking is a cognitive process that occurs in the human brain.

The purpose of this article is not to submit another individual example of these efforts. Rather, we synthesized existing frameworks of geospatial thinking and generated a collective model that represents the conceptual, theoretical, and empirical advances that have been made in the growing area of geospatial thinking. More specifically, our goal is to put forward a model of geospatial thinking that will (1) generate testable hypotheses and (2) represent our current understanding of the relationship between the geospatial thinking skills that have been proposed. The synthesis begins with a meta-analysis of existing frameworks offered by Lobben (2013) in which she identifies existing frameworks, how they individually represent and explain geospatial thinking, and how these frameworks overlap and contradict one another. The synthesized model then integrates all of these existing frameworks, highlighting the strengths and releasing the tension and contradictions. This integration overlays the classic geographic data cube with axes of space, time, and attribute. The synthesized model includes examples of how individual geospatial thinking skills could eventually populate the model. To be sure, though, this placement is somewhat arbitrary. An underlying tenet of this article is that empirical research is needed to place individual skills closer to one axis than another. It is inadequate for us to make assumptions about whether one skill is "more spatial" than another. Therefore, the synthesized model offered here can be considered in two ways. First, the model might eventually illustrate a collective understanding of geospatial thinking and the relationship between individual skills, when that understanding is built on theory-driven empirical research. Second, the model might represent an approach to investigating geospatial thinking more generally. Our proposed reorganization could begin to solve some structural problems illuminated from a meta-analysis of existing frameworks (Lobben 2013). Beyond simply reorganizing, though, we argue that theories of human information processing, based in part on theories in cognitive and neuroscience, not only provide additional understanding of geospatial thinking generally and individual geospatial thinking skills but also expand our traditional geographic toolkit to include brain imaging methods such as functional magnetic resonance imaging (fMRI). These imaging methods, when used in combination with traditional methods in cognitive and behavioral geography research, can identify theoretical correlates between measured performance and brain recruitment and activation associated with individual geospatial thinking skills.

The article ends with a brief presentation of a case study that is offered as an example of how the synthesized model can be used to generate research questions and designs that are informed by the structure of the model itself. The case study uses fMRI and traditional behavioral geography methods to interrogate research questions that are informed by both geography and cognitive neuroscience.

Evolution of Geospatial Thinking Frameworks

Like many constructs and new areas of inquiry, geospatial thinking is evolving. Its initial roots are in ideas that were not originally equated with nor termed geospatial thinking. Identifying the precise generative concept(s) is likely not possible. This dilemma is exacerbated if we consider geospatial thinking as originating from the study or area of spatial abilities. For the purposes of this article, we investigate geospatial thinking where the *geo* is the critical differentiation between the inherently geographic construct of geospatial thinking and more general spatial abilities, intelligence, and thinking. Related literature from other disciplines, namely, psychology, provides a salient perspective on general spatial abilities. As will be unveiled later, however, this synthesis of existing literature centers on geographically focused research and our resulting model is intended for the same audience.

Categorization is one of the basic goals of much scientific research and discussion. Researchers have argued for the importance of defining, organizing, and categorizing geospatial thinking at multiple scales, from the overarching foundation to the individual geospatial thinking skills (Golledge 1992, 1995; Kaufman 2004; NRC 2006; Gersmehl and Gersmehl 2006, 2007, 2011; Marsh et al. 2007; Golledge et al. 2008; Lee and Bednarz 2012). As a result, a single construct of geospatial thinking could be categorized in a multitude of ways, depending on the categorization criteria. In our investigation of the existing geospatial thinking frameworks, two general categories of spatial thinking emerge from the literature. The first category is relevance of geospatial thinking. The importance of not only recognizing but also expanding the role of geospatial thinking in science, technology, engineering, and mathematics (STEM) disciplines has been argued by many scholars (Kaufman 2004; NRC 2006; Gersmehl and Gersmehl 2007, 2011; Golledge et al. 2008; Jo and Bednarz 2009; Goodchild and Janelle

2010; Lee and Bednarz 2012; Logan 2012). The second category is educational application of geospatial thinking. The overwhelming majority of empirical research into geospatial thinking is pedagogically or educationally focused (Kaufman 2004; Marsh et al. 2007; Golledge et al. 2008; Jo and Bednarz 2009; Gersmehl and Gersmehl 2011; Lee and Bednarz 2012).

With both of these categories of geospatial thinking literature, particularly the latter, frameworks of geospatial thinking have been offered as either a theoretical basis for the research (Marsh et al. 2007; Golledge et al. 2008; Gersmehl and Gersmehl 2011; Lee and Bednarz 2012) or a structure within which to conduct research (Kaufman 2004; Golledge et al. 2008; Jo and Bednarz 2009). Although these frameworks often differ substantially, our objective is to provide a geospatial thinking model that is a synthesis of all of the existing frameworks, regardless of original purpose, use, or reason for development. A single model might not ultimately provide the one true foundation for geospatial thinking, but a single synthesized model can unite existing ideas and provide a robust and flexible foundation for geospatial thinking research and discussion. We next provide a brief introduction of the frameworks that were used in the development of the synthesized model.

Using an isotropic plane as the foundation, Nystuen (1968) discussed a framework for a "spatial point of view of geographers" (36). Although his framework might be less formally and concretely structured, his isotropic plane is built on three properties that "are needed to establish a complete geographical point of view" (39). These basic geographic properties include directional orientation, distance, and connectedness. External to those properties and the isotropic plane are some basic geographical problems (history, dimension, time–space, and scale), which are important to categories as they provide a basis on which to gauge similarities between phenomena that might otherwise be perceived as unrelated. Within that structure, he identified several specific constructs: direction, orientation, distance, connection, relative position, pattern, accessibility, neighborhood, and circulation.

Golledge (1992, 1995) expanded and modified Nystuen's base concepts. He proposed primitives of identity, location, magnitude, and space–time. Later, Golledge et al. (2008) provided evidence for the placement of several of the geospatial thinking skills relative to the ordinal scale of complexity along the axes. Their structure is based on increasing complexity of successive geospatial thinking skills, where complexity is based on the number of lower skills needed to reach each subsequently complex skill. They proposed levels or building blocks for geospatial thinking skills: Level One Primitives, Level Two Simple Concepts, Level Three Difficult, Level Four Complicated, Level Five Complex. Further, they offered examples of specific geospatial thinking skills within each category. Subsequent to the development of their building block structure, empirical testing partially validated their initial hypotheses.

Kaufman (2004) proposed an entirely different set of primitives: place, size, shape, distance, direction, connectivity, containment, pattern, duration, sequence, and frequency. He also argued for the inclusion of time. In a project designed to investigate and improve geographic skills of preservice teachers, Kaufman developed a spatial thinking framework based on spatial–temporal primitives. He used this framework as a basis to develop an exercise designed to improve geographic skills. Although not directly developed in his framework, he suggested that his primitives can be used in combination to develop additional geographic skills. For example, size and place can be used to develop understanding of scale, whereas place, containment, and connectivity can be used to develop understanding of site and situation. This suggestion of progressive development represents the complexity construct that has been included in others' spatial thinking frameworks (Golledge et al. 2008; Jo and Bednarz 2009). But, with intention, Kaufman did not fully integrate complexity and the examples provided represent a two-tiered complexity structure.

In another example of a framework constructed on yet another set of primitives, Jo and Bednarz (2009) developed a three-dimensional spatial thinking framework that they applied to evaluate questions in geography textbooks. The three primary axes in their three-dimensional framework were concepts of space, using tools of representation, and processes of reasoning. Their primary axes were then subdivided into categories relevant to each primary axis.

Montello (1993) provided categorical geographic scales. Although he did not offer the scales as a criterion with which to differentiate and organize geospatial thinking skills specifically, the scales are evident within nearly any framework of geospatial thinking. They can be used to distinguish between different geospatial thinking skills. The scales include microscale (i.e., nanoscale, human brain voxels), figural (i.e., personal space—the human body), environmental (the immediate surroundings in which a person engages), and geographic (the area that cannot be perceived from a single location). Working in geographic space often includes engaging with representations of space (i.e., maps, GIS data layers). Many identified geospatial thinking skills are easily differentiated or described through Montello's categories of scale. For example, the skill overlay can take place at a geographic scale. Locating oneself in an environment with the aid of a map, however, is a task that works at multiple scales—environmental (the immediate surrounding area) and geographic (the larger area that is represented by the map). The encoding, storage, and use of a dynamic and ever-changing cognitive map would take place at the microscale (i.e., for measurement and analysis purposes, existing as voxels—volumetric pixels, a system used to organize and measure activity within the human brain, for example).

Finally, adopting a completely different approach to categorization criteria, Gersmehl and Gersmehl (2006, 2007, 2011) provided another framework in which to

Table 1 Examples of geospatial thinking skills

Geospatial thinking skills
accessibility activity space adjacency analogy angle area
arrangement association aura boundary buffer change category
causation center central place change circulation class cluster
comparison connection container correlation corridor containment density
dependence development diffusion dimension direction dispersion
distance distortion distribution dominance duration edge enclosure
enclave extrapolation flow force frequency generalization gradient
great circle grid growth heterogeneity hierarchy homogeneity interpolation
intersection isolation layer linkage location motion movement
neighborhood network object order orientation overlay path pattern
periodicity perspective place polygon prediction profile projection
proximity reference frame relative position representation region relief
rotation scale sequence shape size social area spread subjective space
surface texture transition

categorize and test geospatial thinking. Through a meta-analysis, they identified modes of thinking about conditions at and between places that are both neurologically distinct and "within the neurologic competence of young children" (2007, 181). Their meta-analysis provides support for the development of better geography lessons that were introduced to and evaluated by students and teachers in an early elementary school in Harlem (Gersmehl and Gersmehl 2011). By their own suggestion, they cannot claim causal linkages between end-of-the-year standardized test scores and their spatial thinking exercises. With the group of students engaging in the spatial thinking exercises, however, they did observe dramatic increases in those standardized test scores from the beginning to the end of the year. They also observed dramatic test score differences between their student groups and others from around the city.

Categorization and Organization of Existing Frameworks

The preceding examples reveal several geospatial thinking frameworks that are organized using different categorization schemes. Within these frameworks, individual geospatial thinking skills are categorized. In some cases, the frameworks agree and the same skill is placed in the same category. In other cases, however, the same skills are placed in different categories. The following discussion (from Lobben 2013) reveals the agreement, overlap, and tension between some of these different frameworks and exposes one of the inherent problems with all organizational frameworks—without empirical evidence, the placement of any skill is arbitrary. To begin, Table 1 shows the collective list of discrete geospatial thinking skills pulled from all of the preceding frameworks (Nystuen 1968; Kaufman 2004; NRC 2006; Gersmehl and Gersmehl 2007, 2011; Golledge et al. 2008; Jo and Bednarz 2009; Janelle and Goodchild 2011; TeachSpatial.org 2013).

Most of the skills listed in Table 1 are then parsed out and categorized based on the general organization criteria of each framework. For example, some researchers developed geospatial thinking frameworks that are organized around geographic primitives: identity, location, magnitude, and time (Golledge 1995; Kaufman 2004; NRC 2006; TeachSpatial.org 2013). Table 2 illustrates the organizational approach, with categories of geographic primitives providing the basis

Table 2 *Geospatial skills organized by primitive*

Organized by primitive category			
Identity	**Location**	**Magnitude**	**Time**
boundary, category, class, containment, pattern, place, shape, size, texture	angle, boundary, connection, density, direction, dispersion, distance, distribution, flow, force, intersection, linkage, motion, order, pattern, sequence, shape	frequency, hierarchy	change, development, duration, frequency, growth, periodicity, sequence

Table 3 *Geospatial skills organized by complexity*

Organized by complexity			
Simple	**Difficult**	**Complicated**	**Complex**
adjacency, arrangement, boundary, class, connection, direction, distance, distribution, edge, enclosure, movement, order, proximity, reference frame, region, sequence, shape, transition	adjacency, angle, area, center, change, cluster, grid, growth, isolated, linked, polygon, reference frame, spread	buffer, connectivity, corridor, gradient, profile, representation, scale, surface	activity space, association, buffer, central place, cluster, density, diffusion, distortion, distribution, dominance, enclave, gradient, great circle, hierarchy, interpolation, layer, network, overlay, pattern, profile, projection, relief, scale, social area, subjective space

for identifying similarities between individual geospatial thinking skills. Individual geospatial thinking skills are then assigned to a group or category based on their relationship with the geographic primitive. For example, the skill of containment is assumed to fall within the category of identity. But, Table 2 also reveals instances of the same skill inserted into different categories by different researchers and frameworks. The skills of boundary, pattern, shape, and sequence are duplicated across categories.

Using a different organizational structure, some researchers developed frameworks based on complexity: primitives, simple, difficult, complex (Golledge et al. 2008; Jo and Bednarz 2009). Table 3 illustrates the organizational structure based on complexity. The same individual geospatial thinking skills are then inserted into these resulting categories. Based on the categorization shown in Table 3, we can make assumptions of built complexity, such as the skill of gradient is more complex than profile, which is more complex than change, which is more complex than order. Although in most cases, the individual skills are assigned to different categories, more duplication of skill placement is evident in these frameworks. For example, adjacency, connection or connectivity, distribution, reference frame, cluster, buffer, gradient, profile, and scale are all cross-categorized.

Then, combining all of the overlap, Table 4 reveals all of the individual geospatial thinking skills that are duplicated across categories. This duplication in itself is not the primary concern. Rather, the duplication reveals a bigger issue of general disagreement of the underlying constructs of geospatial thinking. Each of these frameworks is built on a single organizational concept, resulting in different categories, and geospatial thinking skills assigned to groups. Moreover, each of the frameworks creates distinct group boundaries, forcing an in-or-out decision for every geospatial thinking skill.

Following this review of existing frameworks, several questions arise. Which is the best organizing criterion—primitive, complexity, brain area recruitment, or processes of reasoning? Assuming a single organizing criterion, how do we determine the best category in which a geospatial thinking skill belongs? The difficult answers are that all of the criteria provide salient and valid organizational mechanisms, and identifying a single permanent category for each geospatial thinking skill is nearly impossible. The solution is not to develop yet another criterion-based organizational framework with more categories in which the geospatial thinking skills are inconsistently shuffled, however. Instead, a synthesis approach directly and indirectly combines the existing geospatial thinking organizational structures and removes the categorical boundaries to provide more flexibility in placement of individual skills. In other words, the new model is truly synthesized from the previous examples. We combined all of the organizing criteria (i.e., geographic primitive, complexity, and human brain function) and released the rigidity of distinct categories (i.e., developing continuums rather than forcing an in-or-out decision). The next section describes our approach to the synthesized framework.

A Synthesized Geospatial Thinking Model

The synthesized geospatial thinking model is theoretically based on both traditional geographic data concepts as well as human information processing. Situating a framework within both foundations is necessary because geospatial thinking is both geographic—the

Table 4 All overlapping geospatial thinking skills (shown in bold)

Between framework cross-categorized geospatial thinking skills
accessibility activity space adjacency analogy **angle** area
arrangement **association** aura **boundary** buffer **change** category
causation **center** central place change circulation **class** **cluster**
comparison **connection** container correlation corridor containment
density dependence development diffusion dimension **direction**
dispersion **distance** distortion **distribution** dominance duration edge
enclosure enclave extrapolation flow force frequency generalization
gradient great circle grid growth heterogeneity **hierarchy** homogeneity
interpolation intersection isolation layer **linkage** location **motion**
movement neighborhood network object **order** orientation overlay path
pattern periodicity perspective place polygon prediction profile
projection proximity reference frame relative position representation **region**
relief rotation **scale** **sequence** **shape** size social area spread
subjective space **surface** texture **transition**

geospatial—and cognitive—the thinking. The basis of both foundations is discussed next.

Geographic Data Foundation

All of the frameworks discussed earlier, along with the synthesized framework presented later, are focused on geospatial thinking skills. Space is foundational; "[c]rucial to the power of spatial thinking is our ability to use space as a framework for understanding" (NRC 2006, 28). Although space might be a key ingredient in an organizational framework, other criteria must be addressed as well. When describing the three contexts for spatial thinking, the NRC (2006) bring in both the time and attribute criteria. For example, the first context is the everyday world of space–time (the cognition in space), the second context is also situated within space–time and focuses on the cognition about space, and the third context focuses on the relationship between concepts and objects (the geography of our intellectual spaces). Those contexts are neither independent from each other nor dependent on each other. From those structures, we can extract the familiar geographic data characteristics of space, time, and attribute, all of which are also categories in the geospatial thinking frameworks that are organized by primitives (Kaufman 2004; NRC 2006; TeachSpatial.org 2013).

The iconic geographic data cube includes three axes: space, time, and attribute. Although traditionally used to characterize geospatial data, the basic structure and defined axes have been used in the past to provide an organizational structure of geographic constructs (Lobben 2003). In this case, the cube might be adopted to satisfy two problems that arose from the review discussed earlier. By restructuring all of the existing geospatial thinking frameworks within a repurposed geographic data cube, all geospatial thinking skills can at once be organized by primitive (space, time, attribute) and by complexity (relative location to axes origin). Moreover, the restructured framework (Figure 1) is advantaged by the flexibility offered by the data cube axes. Space, time, and attribute are not static, regardless of whether we consider absolute time unidirectional and space and attribute evolutionary (Peuquet 2002) or consider all three primitives continuous, fluid, and changing. Integrating these basic core ideas, categories in the synthesized geospatial thinking model are no longer rigidly defined by binary in-or-out boundaries. Instead, continuums provide placement options for individual geospatial thinking skills. Each axis identifies the origin of a continuum.

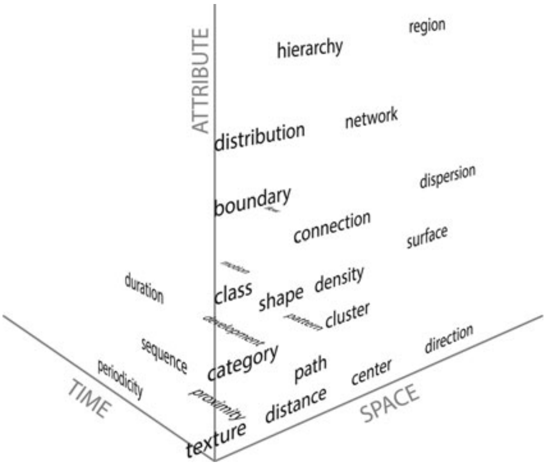

Figure 1 *Synthesized geospatial thinking model.*

As mentioned earlier, Golledge (1992, 1995) originally proposed primitives of identity, location, magnitude, and space–time. We have slightly altered these primitives and assigned them to the structure of our geospatial thinking model. Golledge's primitive *identity* is represented as our axis *attribute*. His primitive *location* is represented in our model by the *space* axis. His primitive *space–time* is included in our model as the *time* axis. His primitive magnitude is not included as a discrete axis. Rather, magnitude is a construct that permeates all of the geospatial thinking skills to different degrees. Magnitude can refer to an actual measured quantity (i.e., a spatial statistics-based geospatial thinking skill), cartographic scale (i.e., comparing two maps at different cartographic), or complexity (i.e., increase in complexity or difficulty of different geospatial thinking skills). Because magnitude is directly related to geographic scale at both a behavioral and neurological level and because geospatial thinking skills necessarily occur at different scales, magnitude is represented as the iterative change along the cube axes.

Individual geospatial thinking skills then populate the framework. The skills are placed along the complexity as well as the primitive axes and continuums. In other words, unlike previous geospatial thinking frameworks, we posit that most of the skills are simply not solely spatial, nor attributional, nor temporal. Instead, most of the skills are defined and developed based on joint influence from two or three of the primitives. Further, some skills might be more related to space and others to attribute. In that case, the skill is placed accordingly—closer to one axis than the other. If researchers determine that a skill is truly based on a single primitive, then that skill can be placed directly on the corresponding axis. Whereas placement relative to axis identifies the space, time, and attribute characteristics, placement relative to origin represents relative complexity. More complex skills are further from the origin. Current placement of the skills in Figure 1 is based on reviewed frameworks already discussed.

Human Information Processing Foundation

Further support for including primitives of space, attribute, and time is generated by basic theories of human information processing. Following their neuroscience and developmental psychology meta-analysis that supported the development of their modes of spatial thinking, Gersmehl and Gersmehl (2007) argued that the human brain maintains "some extraordinarily complex structures for the storage, retrieval, and analysis of information about objects, places, and times" (p. 188). Continuing and extending the important contributions of Gersmehl and Gersmehl (2006, 2007, 2011), our proposed synthesized geospatial thinking model structure is reinforced by theories of human cognitive brain function. Cognitive brain function is defined by the type of information a brain area receives, how the information is transformed by the circuitry of that brain area, and where its output goes (Yantis et al. 2002).

In regard to the visual processing system, two functionally specialized streams that originate from the primary visual area (V1) have been identified: the ventral stream, projecting to the infero-temporal cortex, and the dorsal stream, projecting to the posterior parietal cortex (Figure 2; Milner and Goodale 2008). These two well-known streams of human visual information processing have simplistically been defined as the processor of what-based information (ventral stream) and the processer of where-based information (dorsal stream). Neuroscience research has provided overwhelming evidence that the human brain is wired to categorize what-based and where-based information within these separate but related streams (Valyear et al. 2006).

Current theoretical models of the ventral and dorsal streams are more complex than simply what and where, however, and can best be understood in terms of the output systems that the two streams serve (Milner and Goodale 2008). The dorsal versus ventral model of

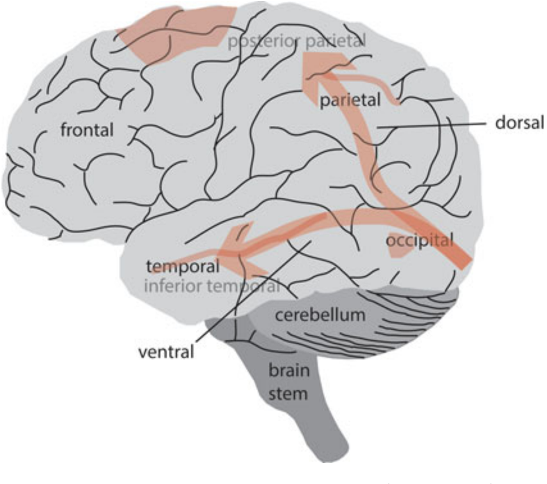

Figure 2 *Dorsal and ventral streams of human information processing. (Color figure available online.)*

visual processing makes a functional distinction between visual information processing for perception versus action. The dorsal and the ventral streams are hypothesized to process information about both the structure of objects (attributes) and their spatial location (space). But the ventral stream transforms input into perceptual representations, allowing us to think about objects and events in the world, whereas the dorsal stream mediates controlled action—like reaching, grasping, and locomotion. These information processing systems are not independent or mutually exclusive—so why would a model of spatial thinking artificially separate them? The multistream processing of what-based and where-based information supports placement of individual geospatial thinking skills between axes, rather than in a single primitive category.

The third axis of our model represents time. Temporal information processing is a fundamental aspect of both perception and action (Nenadic et al. 2003), and it can be argued that there is a temporal dimension to every action we take and every object we perceive (Lewis and Miall 2003). Milner and Goodale (1995, 2006, 2008) argued that the ventral (attribute perception) and dorsal (space–action) processing streams are mediated by time but operate on different timescales. The ventral stream represents an object over time and helps us maintain object characteristics aiding recognition across different viewing conditions. The dorsal stream mediates action toward targets that might change continuously and it works in real time for immediate use of guiding actions (Cohen et al. 2009). The preceding provides evidence for the integration of temporal information processing during what-based and where-based decision making and, thus, neurologically supports the inclusion of time as one of the primitives or axes in our synthesized model.

Temporal information processing refers to a variety of functions, including spatial sequence of events, duration of events, and their temporal order. The field of time perception and temporal information processing is still evolving and the categories of temporal experiences are not yet clearly defined (Grondin 2010). Research, however, has addressed the processing of information in time, timeliness, order (Fuster 1995), motion (Sacks et al. 2006), interval timing (Meck and Malapani 2004), and counting (Pesenti et al. 2000). The neurobiology of temporal cognition is a fairly recent construct (Ivry 1996; Gibbon et al. 1997). The idea of a clock in the brain might best be explained as the mechanism of the central nervous system providing the modality-independent timekeeper function that is required for temporal information processing ranging from milliseconds to seconds (Nenadic et al. 2003), minutes, and beyond. Studies designed to investigate specific neurological activation associated with time-related brain activity using fMRI have produced support for activation in the motor cortex (Lewis and Miall 2002), cerebellum (Clarke et al. 1996), basal ganglia, dorsolateral prefrontal cortex, and the anterior cingulate cortex (Nenadic et al. 2003). Perhaps more important than listing a set of brain areas related to task-specific temporal information processing experiments is highlighting the established relationship between space (dorsal stream), attribute (ventral stream), and time as neurological components that control behavior, support a variety of spatial thinking activities and fuel the inclusion of the three axes in our synthesized geospatial thinking skills model.

Generating and Testing Hypotheses

Regardless of discipline or methods, much scientific inquiry focuses on theoretically structured research questions, hypotheses, and models. Models could be the result of or the stimulus for research. A robust model might provide both. A primary goal of the synthesized geospatial thinking framework is not simply to provide an organizational structure for geospatial thinking skills. Categories are interesting but not necessarily the most effective or most efficient way to generate meaningful and robust research. The geospatial thinking framework described earlier was originally created to provide a foundation for organizing ideas and generating testable hypotheses. A case study is presented briefly, not as empirical research results itself but as an example of research that was generated from our new synthesized framework and then, in turn, provided reorganization to the framework.

Interrogating Complexity and Spatial or Attribute Placement of a Single Geospatial Thinking Skill: Mental Rotation

As some previous geospatial thinking frameworks were organized around complexity of skills, that construct was maintained in this framework. The positioning of skills on the complexity continuum within the model provides a foundation for hypotheses and testing. Ironically, the construct of complexity is itself very complex. We might consider both the between- and within-skill qualities of complexity. Previously, only interskill complexity has been discussed; that is, the order of complexity among the concepts of network, rotation, and region. But what about intraskill complexity; that is, how sensitive are the skills; is there more variability in difficulty between various examples of overlay versus various examples of distance? Also, is intraskill variability noted with regard to the primitive(s) associated with a given skill? In other words, if we keep completely consistent the geospatial thinking skill under investigation, but vary the specific task or graphic, can we measure differences in complexity and in primitive? This question was investigated through a controlled study in which we focused on a single geospatial thinking skill—mental rotation.

This study (summarized from Lobben, Lawrence, and Pickett 2014) was designed to investigate the behavioral and neurological correlates of mental rotation. We conducted two rounds of user testing with human participant volunteers. These participants were asked to complete the same task dozens of times;

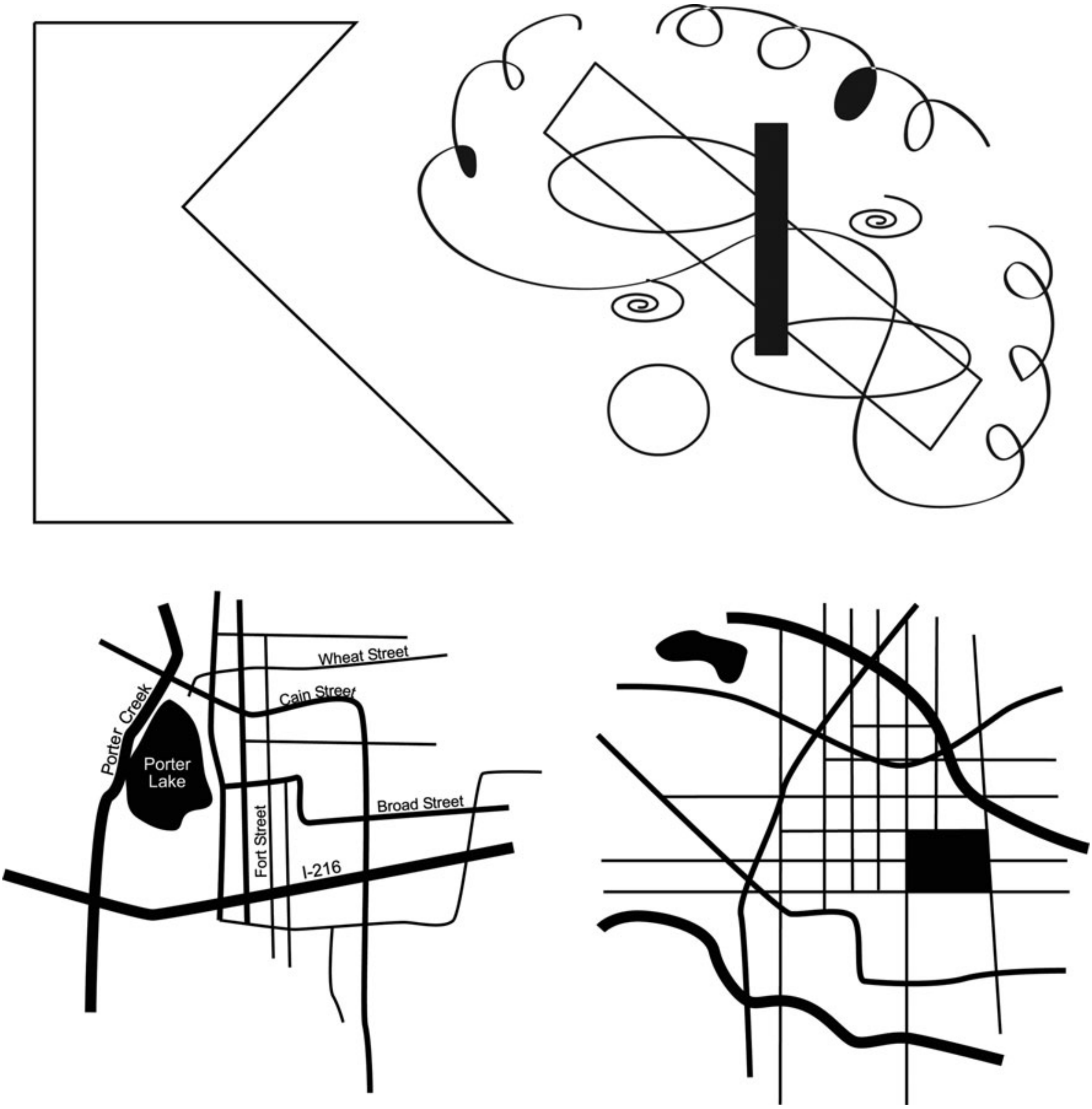

Figure 3 *Example of rotation conditions.*

performance was measured by reaction time—longer times represented lower performance. The task was a simple side-by-side mental rotation exercise. Participants always completed the same task, but we varied the category of stimuli (graphic type). The categories varied based on complexity and space and attribute characteristics.

To investigate the relationships between space and attribute, we created two categories of general geometric objects and two categories of maps (the geometric and map categories are distinguished based on space and attribute differences). To investigate complexity differences, we created a category of simple geometric graphics and a category of complex geometric graphics. Figure 3 represents an example graphic from each category. Behavioral results ($N = 167$) reveal significant performance differences between the categories. For example, the complex geometry condition is significantly more difficult than the simple geometry condition. Additionally, the maps without text condition is significantly more difficult than maps with text.

We followed the behavioral testing with fMRI. Using the same graphics from the simple geometry, maps with text, and maps without text, we collected functional and anatomical images while participants performed the same mental rotation test as before. All experimental conditions (graphic types) reveal activation in the superior parietal lobule and superior or middle frontal gyrus. This finding is similar to a

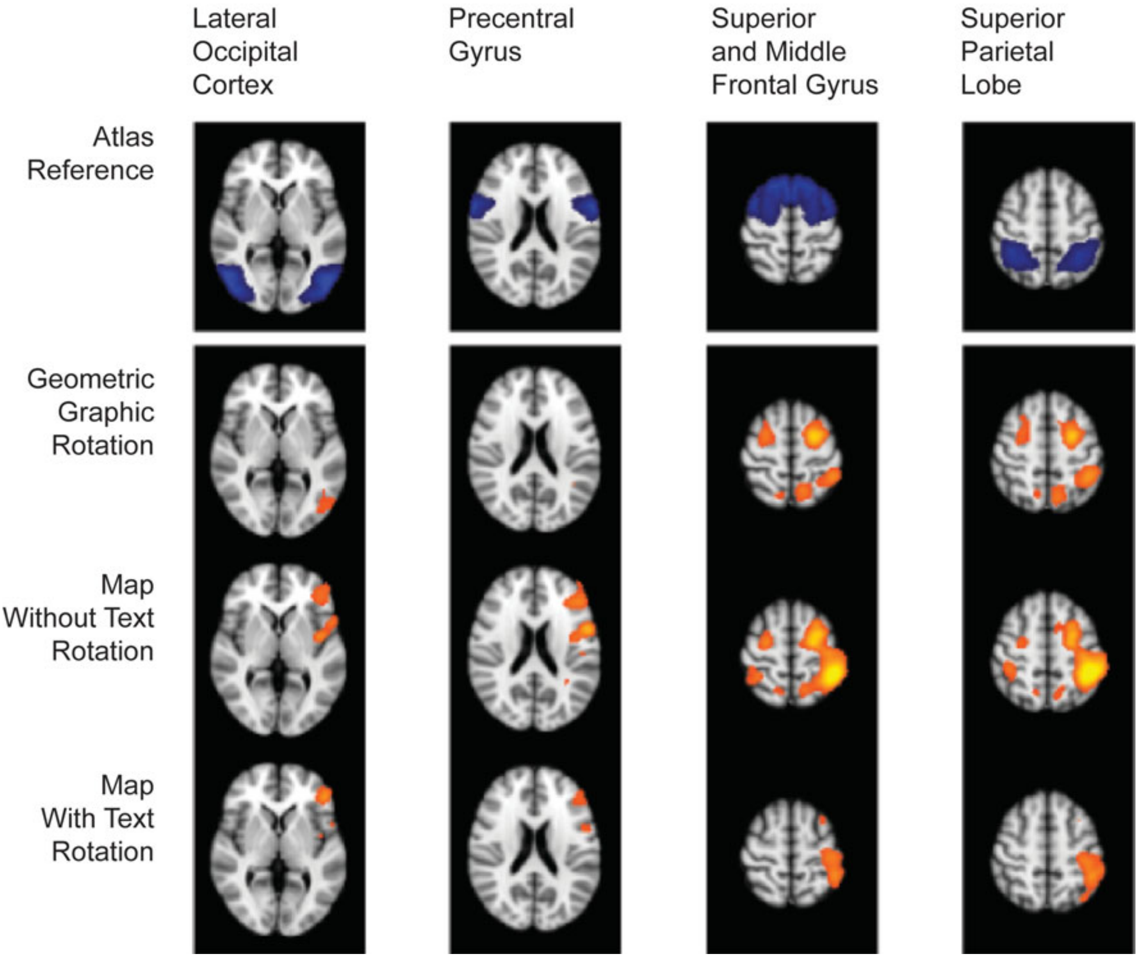

Figure 4 *Activation differences in dorsal and ventral stream areas. (Color figure available online.)*

majority of studies reporting on mental rotation (Clements-Stephens et al. 2009). Our interest here, though, is the extent to which the type of graphics might be associated more with the dorsal than with the ventral stream and therefore, pushing the geospatial thinking skill closer to one axis than the other.

As seen in Figure 4, significant activation differences are also evident. Significant activation is evident in the lateral occipital cortex in the geometric condition but not present in either map condition. Alternatively, activation in the precentral gyrus is evident in both map conditions, but not in the geometry condition. The lateral occipital cortex is part of the ventral stream and known to be recruited for object recognition (Culham et al. 2003). The precentral gyrus, on the other hand, is functionally connected with the parietal lobe as part of the dorsal stream recruited for spatial tasks (Rottschy et al. 2012). The fMRI results also support our behavioral results that show significant complexity differences between the two map conditions. Our results reveal bilateral parietal lobe activation. Similar patterns of activation have been shown in experiments where the difficulty in mental rotation task varies (Pegna et al. 1997; Harris et al. 2000).

So how do these results inform the synthesized geospatial thinking model? Recall some basic tenets of the model. First, the geographic primitives serve as the individual axes in the model. These primitives of space, attribute, and time are directly associated with known functional brain activation, most notably the dorsal and ventral streams. Second, remember that our argument is one of relative, not categorical placement. Third, complexity is represented on the axes continuum relative to the origin. Our results show that all of the experimental conditions resulted in activation in the superior parietal lobe, which is the destination of the dorsal stream (the stream that processes space). Activation strength varies between the conditions, however. Moreover, we identified significant activation in other areas of the dorsal stream for the two map tasks and areas of the ventral stream for the geometric task. We then apply these results to our synthesized model of geospatial thinking and we can suggest that the map tasks are located closer to the space axis and the geometric task closer to the attribute axis. Finally, our results also reveal complexity differences between the conditions. Also applying these results to the synthesized model, we can suggest skill placement relative to the origin.

The purpose of including this research summary is not to explain the details of the study but rather to illustrate how the synthesized geospatial thinking framework outlined in the previous section can be used to generate hypotheses and then be informed by the research results. There is no simple approach. Geospatial thinking research is complicated by the research topic itself. Studying a single geospatial skill brings into the mix both geographic concepts and human information processing. The case study demonstrates that a model that integrates both geographic concepts and cognitive processing could provide the foundation for robust, reliable, and valid research design.

Conclusion

At first glance, the relative placement of individual geospatial thinking skills might appear trivial. Someone might say, “Why should I care whether the skill of ‘region’ is closer to the space, or the time, or the attribute axes?” That placement is very revealing theoretically. If researchers discover that understanding and applying the skill of region is more influenced by space and attribute than it is by time, then we know a substantial amount about that skill. When empirical research compounds discoveries for other skills, an integrated model becomes a powerful visualization of a hugely complex theoretical construct.

Again, whether directly acknowledged or not, all of the conversations surrounding geospatial thinking focus on just that: human thinking. To better understand this growing area within geography, some of the discussion and research should focus on direct human information processing. We are not suggesting that all of the research should be based on neuroimaging. On the contrary, we do suggest that such a complex area of study—how people think about space—is better understood with a multipronged approach to research questions and methodologies. We cannot ask only pedagogic and test performance questions. We cannot ask only brain functioning questions. We cannot only measure children’s test performance, or conduct computer tests, or only measure brain activation, or only measure eye tracking. If researchers continue to investigate geospatial thinking in the variety of ways we have seen to date, and if their results are all feeding from and into a common structure, that structure will continue to be validated (or not). The advantage is that although we might all be asking the questions differently, we are all contributing research back to the same source.

The synthesized model of geospatial thinking presented here is conceptual. It is developed based on ideas and research conducted by others. Because geospatial thinking is a relatively new area of interest in geography, though, this model as well as any other geospatial thinking model will take years to test. In its existing state, the model is both fluid and incomplete. We propose this model as a basis for both ontological organization and hypothesis generation. The basic goal is to provide a framework from which research questions can be generated, whose results will further inform the basic structure and detailed organization within the model. We fully expect that the placement of individual geospatial thinking skills will shuffle and the axes will be changed, removed, or expanded. ■

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AMY LOBBEN is an Associate Professor in the Department of Geography at the University of Oregon, Eugene, OR 97405. E-mail: lobben@uoregon.edu. Her research interests include human–environment interaction, geographic information science, geospatial cognition, neurogeography, and behavioral geography.

MEGAN LAWRENCE is a Senior Research Associate at Cognito, 8636 SE 141st Court, Portland, OR 97086. E-mail: megan@cognito-inc.com. She was a sponsored principle investigator with the Smith-Kettlewell Eye Research Institute when the article was completed. Her research focuses on human spatial behavior and information accessibility for people with disabilities.