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Spatial thinking in geographic information science: a review of past studies and prospects for the future

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Abstract

In recent years, the relationship between geographic information science (GIScience) and spatial thinking has attracted much attention in English-speaking countries. Nevertheless, vagueness remains concerning the concept of spatial thinking and its components. The aim of this paper is to review previous studies on the relationship between GIScience and spatial thinking, and to clarify the elements of spatial thinking and related terms. After discussing the basic elements of spatial thinking, it explores the relationship between GIScience and spatial thinking by dividing it into two aspects: the role of geographic information systems (GIS) in education on spatial thinking, and the role of spatial thinking in GIScience. Concerning the former, potential roles of GIS in spatial thinking education, particularly in geography and STEM disciplines, are suggested. Concerning the latter, the relationships between the body of knowledge on GIS education and the elements of spatial thinking are examined. Finally, the present situation and future prospects for studies on spatial thinking and GIScience in Japan are briefly discussed.

Keywords: geographic information science; spatial thinking; spatial concepts; spatial representations; spatial reasoning;

1. Introduction

Since the National Research Council (NRC) in the United States published a report Learning to Think Spatially [1], the relationship between geographic information science (GIScience) and spatial thinking has attracted interest in English-speaking countries. This is illustrated in the fact that the number of articles that contain the term spatial thinking in the title or keywords, retrieved from an online bibliographic database Scopus provided by Elsevier B.V., has rapidly increased since 2005; in particular, most recent work has been done in the fields of GIScience and geography (including geography education).

This trend reflects various activities of research projects related to spatial thinking. For example, Spatial@ucs (http://www.spatial.ucsb.edu/index.php) is a website established in 2007 at the University of California, Santa Barbara (UCSB) to support research and education concerning spatial thinking. Its
related web site, teachspatial.org (http://www.teachspatial.org/), also provides a variety of tools and materials for teaching and learning spatial thinking. On the other hand, SPLINT (Spatial Literacy in Teaching) in the UK is a project in which three universities participated to enhance spatial literacy skills in higher education (http://www.le.ac.uk/gg/splint/index.html). In addition, SILC (Spatial Intelligence and Learning Center) was established mainly by psychologists to found an integrated, interdisciplinary field of spatial learning and to use the knowledge obtained to improve STEM (scientific, technical, engineering, and mathematical) education (http://www.silccenter.org/index2.html).

In line with this movement in English-speaking countries, a research project that links GIScience to spatial thinking has recently been launched in Japan. In the context of Japan, various researchers in GIScience currently have interest in the effects of proliferation of geographic information technologies, including vehicle navigation systems, navigation with cellular phones, and web mapping, on the mode of spatial thinking. In addition, tools for visualization (e.g., mind maps) have attracted the attention of Japanese businesspersons. This trend may reflect the desire to obtain a complete picture of the complex and globalized conditions of society today.

Nevertheless, vagueness remains concerning the concept of spatial thinking and its components. In particular, since the report of the NRC [1] focused mainly on primary or secondary education, few studies have been made on the role of geographic information systems (GIS) and spatial thinking in higher education and academic research. The aim of this paper is to review previous studies on the relationship between GIScience and spatial thinking, and to clarify the elements of spatial thinking and related terms. We then briefly consider the present situation and future prospects for study of spatial thinking in GIScience in Japan.

2. Definition of spatial thinking and related terms

As spatial thinking is an interdisciplinary subject ranging from psychology and pedagogy to GIScience, no clear consensus yet exists concerning its definition. Accordingly, methods for assessing spatial thinking abilities have not yet been sufficiently developed [2]. This is in contrast to the long tradition of development and use of spatial ability tests in the field of psychology, and raises the question whether spatial thinking can be considered separately from spatial ability.

We provisionally define spatial thinking as a constructive amalgam of three elements: concepts of space, tools of representation, and processes of reasoning, as outlined by the NRC [1, p. 25]. In this paper, these elements are termed spatial concepts, spatial representation, and spatial reasoning, respectively.
The existence of a variety of terms related to spatial thinking, such as spatial literacy, spatial abilities, and graphicy, adds to the vagueness of its definition. To reduce this confusion, we summarize the relationship between these terms as shown in Fig. 1.

Whereas the term spatial literacy has not clearly been distinguished from spatial thinking, we define it as an individual's abilities or attitudes to think spatially in an appropriate way. The NRC [1, p. 4] points out that spatially literate students have the following characteristics:

- They have the habit of mind of thinking spatially.
- They practice spatial thinking in an informed way.
- They adopt a critical stance to spatial thinking.

In contrast, graphicy is a term mainly used in the UK and appears in the Oxford English Dictionary as an entry word at present, being defined as the ability to understand and use a map or graph. This term was presented by Balchin and Coleman [3], who proposed graphicy as a fundamental in education along with literacy, articulacy, and numeracy, which have been emphasized in primary education. Among the elements of spatial thinking, graphicy is closely related to spatial representation. Goodchild [4] also pointed out that spatial thinking as the "fourth R" following the 3Rs (reading, writing, and arithmetic) has become important in today's society, in which a variety of types of spatial information have proliferated with the development of information and communication technologies (ICTs). Hence, graphicy is included in the component of spatial literacy.

Spatial abilities are cognitive skills fundamental to spatial thinking, being composed of spatial visualization, spatial orientation, and spatial relation [5]. A variety of psychological studies have developed and used tests for measuring spatial abilities [6,7]. Since most of them are paper-and-pencil tests in small-scale space, they are not necessarily applicable to spatial thinking in large-scale geographic space. Hegarty and Waller [7], who reviewed previous studies on spatial abilities, found very little correlation between large- and small-scale spatial abilities. This may be due to effects of various factors other than spatial abilities on problem solving in the real-world setting. However, Hegarty et al. [8] indicated that spatial abilities at different scales of space are partially but not completely dissociable. Hence, further investigation is needed to clarify the influence of spatial abilities on spatial thinking. In any case, it is certain that geospatial thinking is founded on spatial abilities.

3. Definition of spatial thinking and related terms

3.1. Spatial concepts

Space provides the conceptual and analytical framework within which data can be integrated, related, and structured into a whole [1, p. 25]. Fundamental to spatial thinking is understanding space by abstracting from it with geometric concepts, viz., distance, coordinates, and dimensions. Since GIScience is mainly concerned with geographic space, it is important to recognize the difference between spatial and geospatial as terms. Golledge et al. [9, p. 286] pointed out that geospatial refers to environmental or geographic scales [10], comprising areas that cannot usually be perceived from a single vantage point on Earth.

Golledge and his collaborators [9,11,12] classified spatial concepts into simple spatial ones (spatial primitives) and complex ones (derivatives) considering the nature of geographic space. Every geospatial concept can be derived from spatial primitives composed of identity, location, magnitude, and (space-)time. A notable feature of this conceptualization is that temporal dimension is included in the primitives, reflecting Golledge's notion of space and time as inseparable elements. Based on these spatial primitives concerning single object, spatial relations between multiple objects can be captured through first-order, second-order, third-order, and fourth-order derivatives step-by-step.

On the other hand, Janelle and Goodchild [13] presented eight foundational concepts for spatial thinking based on the spatial ideas discussed by de Smith et al. [14]: location, distance, network,
neighborhood and region, scale, spatial heterogeneity, spatial dependence, and objects and fields. The first five of these concepts relate to the spatial concepts discussed by Golledge and collaborators, while spatial heterogeneity and spatial dependence as distinctive properties of spatial data identified by Anselin [15] and discrete-object and continuous-field views as two ways of thinking about phenomena on the Earth's surface are regarded as higher-order spatial concepts required for higher or professional education.

3.2. Spatial representation

Internal or external representations provide the forms within which structured information can be stored, analyzed, comprehended, and communicated to others [1, p. 25]. Internal spatial representation is concerned with the formation and manipulation of spatial images in the mind, which requires the spatial abilities of visualization, orientation, and spatial relations. External spatial representation refers to organizing, understanding, and communicating information with maps, pictures, and graphs. The referent of the spatial representation in a broad sense includes not only geographic space but also non-spatial objects that are internally spatialized or externally visualized. In addition, spatial representation is not limited to visual form and includes other forms of sensory modalities, viz., tactile, kinesthetic, and auditory.

Graphicacy is considered a component of spatial representation. Broadman [16] shows the skills in graphicacy to be learned in primary or secondary education, divided into six grades. While Broadman emphasized the use of maps, Bertin [17] presented the concept of visual variables in various kinds of graphic representations. MacEachren [18] provides useful information of geovisualization which emphasizes new methods for spatial representation with ICTs. In addition, findings from cognitive cartography [19] and spatial languages [20] are also applicable to examination of the properties of internal aspects of spatial representations.

3.3. Spatial reasoning

Reasoning processes provide the means of manipulating, interpreting, and explaining structured information [1, p. 25]. Spatial reasoning is involved in the higher-order cognitive process of inference from prior knowledge to solve problems or make decisions. While the same term is used in computer science, the meaning of this term is broader in GIScience.

Jo and Bednarz [21] classified spatial reasoning into three levels: input level, with gathering of information from the senses or recalling information from memories; processing level, in which learners analyze, classify, explain, or compare information acquired at the input level; and output level, featuring generation of new knowledge or products from the information obtained from the first two levels. In other words, spatial reasoning is considered a complex process integrating the other elements of spatial thinking.

Though the general models of reasoning or problem-solving are deduction and induction, many tasks in goal-oriented thinking with GIS involve "abduction," which builds exploratory hypothesis from empirical data [22]. GIS, which enables the solution of real-world problems by processing of geospatial information interactively or visually, is particularly useful for abductive reasoning. For example, Dr. John Snow's investigation of a cholera outbreak in mid-nineteenth century London can be regarded as a product of abduction. As you know, he conceived the hypothesis that cholera was transmitted through polluted water rather than the air, as was commonly believed. This hypothesis was created and tested by mapping the distribution of cholera deaths and water pumps. It is obvious that the reasoning process in this involves three elements of spatial thinking [1, p. 14].

Nevertheless, theoretical or empirical investigation of spatial reasoning has made even less headway in cognitive science than the other two elements of spatial thinking. Since spatial reasoning is often involved in the practical application of spatial thinking, it should be examined concretely based on each setting of problem-solving or decision-making.
4. Spatial thinking and GIScience

At least two aspects of the relationship between spatial thinking and GIScience can be distinguished. First, GIS is regarded as a tool of ICT supporting education in spatial thinking. The latter part of the report of the NRC [1] emphasized the usefulness of GIS in teaching or learning spatial thinking in primary and secondary education. This aspect can be termed spatial thinking with GIS.

Second, spatial thinking has become a conceptual foundation for GIScience because it is indispensable for systematizing the body of knowledge of GIScience and GIS use. We refer to this aspect as spatial thinking in GIS.

In this section, after outlining the conditions of spatial thinking education from primary schools to universities, we examine the role of GIS in teaching and learning spatial thinking, and review the relationship between GIScience and spatial thinking.

4.1. Education of spatial thinking at elementary or secondary schools

As the NRC [1] pointed out, spatial thinking is taught and learned not only in geography but also in other subjects (e.g., mathematics and science) in the K-12 curriculum of the US. In addition, in Japanese primary and secondary education, units concerning spatial thinking in textbooks and official guidelines for school teaching can be found for geography (consolidated into social studies in elementary school), arithmetic/mathematics, and science. Specifically, fundamental spatial concepts are taught in units on figures or geometry [23], while practical applications of these concepts are included in units on geography and science. Therefore, cooperation between these subjects is preferable for effective training of spatial thinking. Among these subjects, geography plays the role of application of spatial thinking to real-world settings. Jo and Bednarz [21], who analyzed the contents of four high school level geography textbooks in terms of the three elements of spatial thinking, reported that textbook questions focus on low-level spatial concepts, require little spatial representation, and rarely encourage higher-order spatial reasoning. They concluded that teachers need to design advanced questions integrating the three elements of spatial thinking.

To meet these demands, Gersmehl [24] developed multimedia teaching material entitled "Teaching Geography" and supported by the Association of American Geographers. This material provides a variety of resources for teaching spatial thinking skills in classes on world geography. Specifically, it distinguishes the following eight modes of spatial thinking based on findings of neuroscience and developmental psychology [24,25]: comparison, aura (influence), region, hierarchy, transition, analog, pattern, and association (correlation). These modes can be associated with the components of spatial concepts presented by Golledge as mentioned above, and are applicable to higher education as well as primary and secondary education.

4.2. The role of spatial thinking in higher education and academic research

It has been pointed out that spatial thinking plays a significant role in higher education and academic research, particularly in the so-called STEM disciplines [26]. For example, many studies have reported that students' spatial abilities are significantly correlated with success in areas of science and technology such as chemistry, physics, and biology [27,28,29,30]. According to the NRC [1, p. 47], spatial thinking in science progresses through the following three steps:

- extracting spatial structures
- performing spatial transformations
- drawing functional inferences.

Difficulty increases in this order due to addition of the spatial dimension to be considered.
In particular, geoscience research involves highly sophisticated processes of spatial thinking. Kastens and Ishikawa [31] summarized cognitive tasks required for spatial thinking in the geosciences, which partially overlap with the three elements of spatial thinking mentioned above.

On the other hand, the importance of spatial thinking has also increased in social sciences since its "spatial turn" [32], which has been accelerated by the ICTs including the Center for Spatially Integrated Social Science, which was founded in 1999 at UCSB and has promoted sharing of analytical tools for spatial thinking in the social sciences. In particular, its SPACE (Spatial Perspectives on Analysis for Curriculum Enhancement) program has provided undergraduate instructors with workshops to advance spatial thinking in the social sciences [33].

4.3. The role of GIS in teaching and learning about spatial thinking

The principal aim of the report of the NRC [1] was to demonstrate the validity of GIS in teaching and learning spatial thinking. However, no studies have empirically verified the effects of GIS other than Lee and Bednarz [34], who examined the effects of GIS learning on the spatial thinking ability of college students.

Some researchers have thrown doubt on the effect of GIS teaching in primary education. For example, Marsh et al. [35, p. 97] pointed out that use of existing GIS software bears the risk of teaching point-and-click procedures and proposed the concept of Minimal GIS; its three principles should

- be based primarily on concepts, not methodologies
- consist of a set of concepts that are ordered in sequence from basic and low-tech to those that are computational and high-tech
- provide the basis for spatial thinking and the ways that spatial information can be extracted from data by manipulation and/or representation.

Hence, they argued that GIS teaching, particularly in early grades, need not necessarily involve a computer or complex software package. Golledge and collaborators [9,35] tested tasks corresponding to the five levels of geospatial concepts mentioned above.

Skills in spatial thinking are acquired not only at schools but also through everyday life. For example, Newcombe [26] pointed out that children's spatial thinking improves with play, such as paper folding and computer games, and is influenced by the home environment. Hazama [23] argued that this also has lead to underestimation of the importance of teaching of spatial thinking in school mathematics in Japan.

In any case, it is obvious that the need for teaching and learning of spatial thinking has increased with the rapid growth and widespread use of geospatial technologies. There is little doubt that in-depth understanding of the spatial concepts behind GIS is important for appropriate use of geospatial technologies.

4.4. Spatial thinking in GIScience

The study of cognition has been a fundamental research domain of GIScience. For example, it was one of the 13 topics in the list of research priorities listed by the University Consortium for Geographic Information Science (UCGIS) [36]. Spatial thinking is included in major areas of cognitive research in GIScience identified by Montello [37].

The UCGIS published Geographic Information Science & Technology Body of Knowledge [38] (abbreviated here as U-BoK) to provide a comprehensive outline of the concepts and skills that need to be learned mainly in higher education in the GIS&T fields. Based on it, Yasushi Asami and his group prepared a Japanese version of BoK (abbreviated here as J-BoK) (http://curricula.csis.u-tokyo.ac.jp/bok201006.pdf). However, BoK does not explicitly indicate its relationship to spatial thinking. We summarize the relationship between the units of BoK and the elements of spatial thinking in Table 1. This table demonstrates that most of the units of BoK are involved in spatial thinking.
For example, the georeferencing included in the unit of "Geospatial data" in U-BoK and "Transformation and management of spatial data" in J-BoK is related to spatial thinking. Georeferencing requires understanding of abstract frame of reference based on Euclidian geometry.

The units of "Cartography and visualization" in U-BoK and "Visual representation of spatial data" in J-BoK are closely related to spatial representation. Various techniques for making thematic maps included in these units lead to effective communication and discovery of hidden information in geospatial data.

Spatial reasoning is supported by a variety of methods of spatial analysis. For example, network analysis included in the units of "Analytical methods" in U-BoK and "Spatial analysis" in J-BoK enables inferences regarding spatial relations by searching for the optimum route under a given condition and solving problems combining other methods of spatial analysis with GIS.

Table 1. Relationship between the categories of GIScience BoK and the elements of spatial thinking

<table>
<thead>
<tr>
<th>BoK (UCGIS)</th>
<th>BoK (Japan)</th>
<th>Elements of spatial thinking</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conceptual foundations, Geospatial data</td>
<td>Modeling and formalizing spatial data</td>
<td>Concepts: *</td>
</tr>
<tr>
<td>Design aspects, Data modeling</td>
<td>Acquisition and production of spatial data</td>
<td>Representation: *</td>
</tr>
<tr>
<td>Data manipulation</td>
<td>Transformation and management of spatial data</td>
<td>Reasoning: +</td>
</tr>
<tr>
<td>Analytical methods, Geocomputation</td>
<td>Spatial analysis</td>
<td></td>
</tr>
<tr>
<td>Cartography and visualization</td>
<td>Visual communication of spatial information</td>
<td></td>
</tr>
<tr>
<td>GIS&amp;T and society, Organizational and institutional aspects</td>
<td>GIS and society</td>
<td></td>
</tr>
</tbody>
</table>

Note: *: strong relationship; +: weak relationship.

5. Recent efforts to integrate spatial thinking and GIS education in Japan

The term spatial thinking is not yet in widespread use in GIScience in Japan. For example, only 39 articles including this term in their titles were retrieved from an online bibliographic database CiNii, provided by the National Institute of Informatics (as of December 2010). In addition, most of the articles retrieved related to school education in arithmetic/mathematics. However, numerous studies on spatial cognition have been made by researchers in GIScience, as well as in psychology and cognitive science. Specifically, investigation of map reading/use and wayfinding/navigation has rapidly grown with the dissemination of in-vehicle navigation systems and location-based services in Japan [39,40].

Nevertheless, examination of the role of spatial thinking in GIS education and GIScience has only recently begun in Japan. Currently, a research project supervised by Yasushi Asami and supported by the Center for Spatial Information Science (CSIS) at the University of Tokyo is attempting to produce a Japanese version of BoK and develop teaching materials for spatial thinking in GIScience. The present paper is a product of this project, and has been prepared to establish a conceptual basis for spatial thinking in GIScience through review of previous studies in English-speaking countries.

In this section, we report results of a survey conducted to examine Japanese perceptions of the concept of spatial thinking. We asked 40 people who attended an annual symposium held by CSIS at the University of Tokyo to provide the following information:
• three typical situations in their daily lives or specialty areas that require spatial thinking
• three examples of tasks that require spatial thinking in the use of GIS or in the field of GIScience.

Of the respondents, 15 were researchers or teachers at a university, junior college, or technical college; 14 were students; 5 were in industry or public service; and 6 were (local) government officials.

Table 2. Examples of spatial thinking in daily life and GIS use

<table>
<thead>
<tr>
<th>Daily life</th>
<th>n</th>
<th>GIS use</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wayfinding or route planning</td>
<td>30</td>
<td>Spatiotemporal analysis</td>
<td>40</td>
</tr>
<tr>
<td>Walking, driving a car</td>
<td>17</td>
<td>Map use and making</td>
<td>8</td>
</tr>
<tr>
<td>Map use and making</td>
<td>12</td>
<td>Spatial scale</td>
<td>6</td>
</tr>
<tr>
<td>Spatiotemporal analysis</td>
<td>10</td>
<td>Wayfinding</td>
<td>4</td>
</tr>
<tr>
<td>Description or identification of place</td>
<td>9</td>
<td>Layer operation</td>
<td>3</td>
</tr>
<tr>
<td>Sorting of furniture or packaging</td>
<td>7</td>
<td>Photogrammetry/remote sensing</td>
<td>3</td>
</tr>
<tr>
<td>Jigsaw puzzle</td>
<td>2</td>
<td>Description or identification of place</td>
<td>2</td>
</tr>
</tbody>
</table>

Concerning their experience in GIS (with multiple responses allowed per respondent), 25 people had used GIS software for research or at work; 22 were conducting research on GIS or GIScience; 17 had taken classes in GIS or GIScience at a university (or elsewhere); 11 had given classes in GIS or GIScience at a university (or elsewhere); 11 had developed GIS or geospatial data; and 3 had sold or disseminated GIS or geospatial data. These attributes of the respondents show that they engage in the use or teaching of GIS in some way or other, and that they have high degrees of interest and experience in GIS.

Answers to the questions about spatial thinking are summarized as Table 2.

Concerning the responses to the first question (situations in daily lives or specialty areas that require spatial thinking), 30 responses noted wayfinding or route planning; 17, movement in space such as walking or driving; 12, the use or making of maps; 10, various spatial (or spatiotemporal) analyses; 9, the description or identification of places; 7, setting of furniture in a room or packing of things in a suitcase or box; and 2, solving jigsaw puzzles.

Concerning responses to the second question (tasks that require spatial thinking in GIS), 40 responses noted various spatial (or spatiotemporal) analyses; 8, the use or making of maps; 6, operations related to spatial (or map) scale; 4, wayfinding or route planning; 3, layer operations such as buffering or overlay analysis; 3, remote sensing or photographic surveying; and 2, the description or identification of places.

These responses show that people associate concrete spatial behavior in their daily lives, such as navigation and wayfinding in space, with the act of thinking spatially. Together with this finding, findings in the literature on spatial cognition and behavior in real space may provide theoretical and practical insights. Concerning spatial thinking specifically related to the use of GIS, many responses noted various forms of descriptions and analyses of spatial distributions, suggesting that people consciously consider the purposes of using GIS (objectives of research or what is studied). Concrete tasks concerning GIS use, such as mapping, scaling, and layer operations, were also frequently mentioned. Many of these issues were discussed in past research on GIS and spatial thinking [9,13,25], though in future study it will be important to consider methods for assessing or measuring abilities related to these spatial thinking skills.
6. Conclusions

As described in this paper, spatial thinking affords the conceptual foundation of GIScience and increases the applicability of GIS to teaching and learning spatial thinking. However, at least two types of questions still need to be considered.

First, empirical testing of the roles of GIS in enhancing spatial-thinking skills is insufficient. For example, as mentioned earlier in this paper, how spatial abilities tested in small-scale spaces are transferable to geospatial thinking in large-scale environments is still open to question. This question thus concerns whether GIS learning develops generic skills or discipline-specific (or domain-specific) knowledge. If the relationship between large- and small-scale spatial abilities is verified, skills acquired through GIS learning could be transferable to broader areas of spatial thinking.

Second, further investigation of the relationship between the components of GIS&T BoK and the elements of spatial thinking is needed, although we attempted to clarify the elements of spatial thinking and related terms in this paper. In particular, it is possible that GIS, while supporting spatial thinking, also makes it a "black box" in effect. Hence, the demand for the teaching of spatial concepts behind GIS to the user has been growing. These issues require theoretical and empirical examinations on the basis of findings in the literature of cognitive science and other related fields.

References


