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The components of spatial thinking: empirical evidence

Robert S. Bednarz[a*], Jongwon Lee[b]

[a]*Department of Geography, Texas A&M University, College Station, Texas, USA 77843-3147*
[b]*Dept. of Social Studies Education. Ewha Womans University, Seoul, South Korea 120-750*

Abstract

This paper begins with a short discussion of concepts of spatial thinking skills and the instruments available to measure them. Next, the paper briefly describes the development of the Spatial Thinking Ability Test (STAT). Differences in the performance of 446 junior high, high school, and university students are explored and tested for statistical significance. In addition, the test scores are analyzed using factor analysis to identify underlying spatial thinking components and to determine if the identified components support the structure of spatial thinking proposed by other researchers. Students at all levels displayed similar performance patters; scores for all students were uniformly higher for some questions than others, offering some support for the argument that spatial thinking is composed of more than one skill or ability (in addition to the widely accepted spatial visualization and orientation abilities). We hypothesized that factor analysis would identify independent components of spatial thinking by generating factors that reflected the eight components of previous researchers' spatial thinking conceptualizations that were represented by questions in the STAT. Our analysis of STAT scores, however, offers relatively little support for the existence of the independent spatial thinking components hypothesized in the literature. The analysis does suggest that spatial thinking is almost certainly not a single ability but comprised of a collection of different skills. Based on the clusters indentified by the analysis, the following spatial thinking components emerge: map visualization and overlay, identification and classification of map symbols (point, line, area), generalized or abstract Boolean operations, map navigation or way-finding, and recognition of positive spatial correlation.

Keywords: spatial thinking; visualization; spatial relations; orientation; Spatial Thinking Ability Test;

1. Introduction

During the last decade, spatial thinking has received considerable attention from scholars in geography and other disciplines. In part, this new interest was sparked by the publication of *Learning to Think Spatially* from the National Research Council's Committee on Spatial Thinking [1]. The study's authors, academics from a variety of disciplines including geography and psychology, argued that spatial thinking is an amalgam requiring the spatial thinker to understand three related components: the nature of space, the methods used to represent spatial information, and the processes of spatial reasoning [1]. Their

* Corresponding author. Tel.:+ 1-979-845-7187; fax:+ 1-979-862-4487.
E-mail address: r-bednarz@tamu.edu.

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definition of spatial thinking is not as narrow as the customary definition of spatial abilities. Spatial ability has been studied extensively, mostly by cognitive psychologists, who agree that two dimensions, spatial visualization and spatial orientation, comprise the ability. Whether (an)other dimension(s) exist is still an open question. Besides visualization (the ability to mentally represent and operate on visual stimuli) and orientation (the ability to picture spatially arrayed elements from different perspectives), some researchers, especially geographers, have proposed that a third spatial thinking dimension involves understanding spatial relations [2,3,4,5]. Golledge and Stimson [3] were among the first to propose a definition of spatial relations.

> Spatial relations include 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.

In this paper, we adopt the definition of spatial thinking offered by *Learning to Think Spatially,* in part to avoid the argument about whether spatial relations constitutes an ability, aptitude or a thinking skill.

Psychometric, pen-and-pencil tests have been used successfully by researchers to assess subjects' visualization and orientation abilities at a table-top scale [6,7]. These tests left geographers, earth scientists, and environmental scientists dissatisfied because they referred to a scale that was not the most relevant for their disciplines and because they did not test spatial relations, a dimension important to understanding real-world spatial patterns and processes [8,9,10].

In addition to the lack of a spatial thinking assessment instrument, the literature also reveals a substantial disagreement about the nature of cognitive processes involved and about the number of major components of spatial thinking and about the relationship, if any, between spatial ability and spatial thinking. This lack of consensus, however, has not prevented researchers such as Gersmehl & Gersmehl [11,12], Golledge [13,14], and others [15,16,17] from proposing hierarchies or constituent components of spatial thinking skills and concepts. For example, Gersmehl & Gersmehl [11,12] offered a taxonomy of spatial thinking defined as skills that geographers use to analyze the spatial relationships in the world. The Gersmehls listed several modes of spatial thinking and argued that brain research suggests that these modes have distinct or independent neurological foundations. As their definition of spatial thinking suggests, the skills they identified focused only on those used at a geographic scale (e.g., map interpretation, geographic analysis, etc.).

2. Development and results of the Spatial Thinking Ability Test

To address the lack of an instrument to assess the components of spatial relations and, more broadly, spatial thinking, we created, pilot-tested, and refined the Spatial Thinking Ability Test (STAT). Questions were created to assess the spatial thinking components identified by Gersmehl and Gersmehl [12] and by Golledge et al. [18]. We were not able to include questions that addressed Janelle and Goodchild's components because the STAT was developed before their work was available. Nevertheless, Janelle and Goodchild's proposed spatial thinking structure is similar to those of Gersmehl and Gersmehl [12] and Golledge et al. [18] (Table 1). It should be noted that in this table we have summarized the components identified in these studies, especially those listed by Golledge et al. [18], to highlight the similarities. We have attempted to reflect the authors' intentions as accurately as possible in constructing this table.

The Spatial Thinking Ability Test consists of a series of multiple-choice questions that assess a wide range of spatial thinking skills. Two equivalent forms of the test were created so that it could be administered as a pre- and post-test when appropriate. For a more complete discussion of the development of the STAT and discussion of test results see the forthcoming article in the *Journal of Geography* by Lee and Bednarz [19].

Table 1. Spatial thinking concepts suggested by Gersmehl and Gersmehl [12], Golledge et al. [18], and Janelle and Goodchild [17] (after Lee and Bednarz [19])

Gersmehl & Gersmehl	Golledge et al.	Janelle & Goodchild
Condition	Identity	Objects and Fields
Location	Location	Location
Connection	Connectivity	Network
Comparison	Distance	Distance
Aura	Scale	Scale
Region	Pattern Matching	Neighborhood and Region
Hierarchy	Buffer	Spatial Dependence,
Transition	Adjacency, Classification	Spatial Heterogeneity
Analogy	Gradient, Profile	
Pattern	Coordinate	
Spatial Association	Pattern, Arrangement, Distribution, Order, Sequence	
	Spatial Association, Overlay/Dissolve, Interpolation	
	Projection, Transformation	

The STAT has been used in a wide variety of environments with a diverse set of students. The results reported here pertain to a sample of 446 test-takers, 52 secondary, 149 tertiary, and 245 university students. As might be expected, university students performed best, averaging 10.7 correct answers out of a possible 16. High school students scored next best, averaging 7.6 correct answers, followed by secondary students who averaged 4.6 correct answers. The average item score for tertiary students exceeded the average score of secondary students for every test question. In contrast average item scores of students from two of the four universities fell below the average question scores of tertiary students for a few items.

Perhaps more interesting is that the average item scores for students at all levels varied consistently. That is, the questions on which secondary students scored lowest (or highest) were also the items on which high school and university students scored lowest (or highest). We were also interested in the performance of geography majors versus non-majors among the college students. The geographers answered more questions correctly on average than the other students (11.8 and 10.3, respectively), but the difference was not statistically significant ($p = 0.07$). Comparing average scores of university students by gender also yielded a statistically insignificant difference. Males scored only slightly better than females, 10.4 versus 10.0 ($p = 0.18$).

During the development of the Spatial Thinking Ability Test, we were somewhat concerned about the internal consistency of the test as measured by Cronbach’s alpha. Only after revising the test and eliminating some questions did the value of the statistic exceed 0.7, the magnitude frequently used as the threshold indicating test items are reliably consistent. Upon further reflection and as the work concerning the structure or components of spatial thinking described previously appeared in the literature [12, 17, 18], it seemed more and more likely that spatial thinking, unlike visualization and orientation, was not a single ability but a collection of skills. If these skills represented components of spatial thinking that were at least somewhat independent, then it is understandable that the STAT’s internal consistency might not be as strong as one would otherwise expect.

Because the questions that make up STAT were designed to assess the spatial thinking components identified in the structures and hierarchies proposed by Golledge et al. [18] and Gersmehl and Gersmehl

[12] and because the components suggested by Janelle and Goodchild [17] are similar, we realized that the test results comprised a data set that could be used to explore first, the extent to which spatial thinking skills are composed of identifiable components and second, whether the components aligned with those proposed by previous researchers. As noted earlier, students at all levels consistently found some thinking skills more challenging than others. This result offers some support for the proposition that spatial thinking skills are composed of different components, that is, because an individual is proficient a one (or more) particular thinking skills does not imply that she or he will be adept at others.

3. Factor analysis

To analyze the test scores more extensively, we performed factor analysis in an attempt to discover the intercorrelations between the test items. Our hope was that the resulting factors would consist of items that pertained to an identifiable skill or component of spatial thinking. For example, if all the test items assessing skills associated with recognizing similar spatial patterns and spatial correlations loaded highly on one factor, this result could be interpreted to support the proposition that one component of spatial thinking consisted of identifying spatial association or spatial dependence. In addition to isolating a component of spatial thinking, this result could also be seen as support for the conceptualizations of spatial thinking offered by Golledge et al. [18], Gersmehl and Gersmehl [12], and Janelle and Goodchild [17].

Factor analysis of the 16 questions, representing eight spatial thinking components (navigating using direction and location information, detecting map patterns, understanding map layers, interpreting a topographic map, identifying spatial correlation, visualizing a 3-dimensional image, converting verbal and symbolic information to spatial information, understanding map overlays and dissolves), yielded 6 factors with eigen values of 1.0 or more. These factors accounted for almost 60 percent of the variance.

Two of the six factors, the second and third accounting for 10.7 and 10.5 percent of the variance, respectively, can be interpreted as groups of skills related to one of the eight components listed previously. Four of the questions that load highly on the second factor relate to the use of verbal and symbolic information to understand spatial patterns and images. Of the five question types that load highly on the third factor, four are associated with understanding overlays and the fifth is related to what might be considered a similar skill, identifying spatial correlation. The remaining four factors paint a more confusing, less consistent picture. Four questions load heavily on the first factor, but each of the questions is related to a different spatial thinking component. Only two questions are grouped with factor 4, and they represent different components while just one question loads on the remaining factors.

4. Conclusions

These results offer little support for the existence of the eight spatial thinking components incorporated into the STAT's questions. Neither do they provide confirmation of the spatial thinking structure or hierarchies proposed in previously published research, on which the STAT was based. To be clear, we do not assert that the results of the factor analysis are conclusive nor that the Spatial Thinking Ability Test is the optimal assessment instrument for uncovering the components of spatial thinking. For example, previous research has found that some individuals use verbal strategies to solve spatial problems so it is possible that the problem-solving techniques used by students might have influenced their performance. Aside from issues related to the construction or accuracy of the STAT, other factors might explain why the analysis did not yield eight factors representing the eight hypothesized spatial thinking components. First, it may be that fewer than eight components constitute spatial thinking, and those proposed in previous research and reflected in the STAT's questions may not be among them. Furthermore, even if the hypothesized components are relevant and meaningful, they may not be sufficiently independent to allow the analysis to identify factors representing each component.

Although the results generated by the factor analysis do little to confirm previous hypotheses about the structure of spatial thinking, the analysis did produce five factors that are composed of somewhat coherent sets of spatial thinking skills. Three of the four questions loading on first factor are related to map-visualization and overlay, and four of those loading on the second factor assess the ability to discern the difference between point, line, and area symbols on maps. The third factor is composed of questions associated with comprehending mapped patterns and performing Boolean operations on map-like diagrams. The final two factors result from single questions, a navigation task on a street map and the identification of positive spatial correlation, respectively.

We do not assert that the five factors identified by our exploration of the Spatial Thinking Ability Test results represent the definitive components of spatial thinking. Nevertheless, we do think these findings are significant because they are based on empirical data and because they strongly suggest that spatial thinking is not composed of a single skill. More specifically, the results support the proposition that spatial relations (as proposed by Golledge [3] and similar conceptualization offered by others) is not an ability similar to visualization or orientation but a collection of skills and aptitudes. This research has taken only a first step towards identifying and understanding what are the components of spatial thinking, but it is an important first step based on a relatively large and diverse data set.

References

[1] National Research Council Committee on Spatial Thinking. *Learning to think spatially*. Washington DC: NRC; 2006.

[2] Gilmartin PP, Patton JC. Comparing the sexes on spatial abilities: Map-use skills. *Annals of the Association of American Geographers* 1984; **74**(4): 605-19.

[3] Golledge RG, Stimson RJ. *Spatial behavior: a geographic perspective*. New York: The Guilford Press; 1997.

[4] Lohman DF. *Spatial ability: A review and reanalysis of the correlational literature.* Technical report 8. Stanford University, Aptitude Research Project, School of Education; 1979.

[5] Montello DR, Lovelace LL, Golledge RG, Self CM. Sex-related differences and similarities in geographic and environmental spatial abilities. *Annals of the Association of American Geographers* 1999; **89**:515-34.

[6] Goldstein D, Haldane D, Mitchell C. Sex differences in visual-spatial ability: the role of performance factors. *Memory & Cognition* 1990; **18**(5): 546-50.

[7] Newcombe N, Dubas JS. A longitudinal study of predictors of spatial ability in adolescent females. *Child Development* 1992; **63**: 37-46.

[8] Golledge RG. Geographical perspectives on spatial cognition. In: Gärling T, Golledge RG, editors. *Behavior and environment: psychological and geographical approaches*. Amsterdam: Elsevier Science Publishers; 1993, p. 16-46.

[9] Lee J, Bednarz RS. Effect of GIS learning on spatial thinking. *Journal of Geography in Higher Education* 2009; **33**(2):183-98.

[10] Self CM, Gopal S, Golledge RG, Fenstermaker S. Gender-related differences in spatial abilities. *Progress in Human Geography* 1992; **16**:315-42.

[11] Gersmehl PJ, Gersmehl CA. Wanted: A concise list of neurologically defensible and assessable spatial-thinking skills. *Research in Geographic Education* 2006; **8**:5-38.

[12] Gersmehl PJ, Gersmehl CA. Spatial thinking by young children: neurologic evidence for early development and "educability". *Journal of Geography* 2007; **106**:181-91.

[13] Golledge RG. Primitives of spatial knowledge. In: Nyerges TL, Mark DM, Laurini R, Egenhofer MJ, editors. *Cognitive aspects of human-computer interaction for geographic information systems*. Kluwer Academic Publishers, Boston; 1995, p. 29-44.

[14] Golledge RG. The nature of geographic knowledge. *Annals of the Association of American Geographers* 2002; **92**(1): 1-14.

[15] Battersby S, Golledge RG, Marsh MJ. Incidental learning of geospatial concepts across grade level: map overlay. *Journal of Geography* 2006; **105**:139-46.

[16] Marsh M, Golledge R, Battersby SE. Geospatial concept understanding and recognition in G6-college students: a preliminary argument for minimal GIS. *Annals of the Association of American Geographers* 2007; **97**(4):696-712.

[17] Janelle DG, Goodchild MF. Location across disciplines: reflection on the CSISS experience. In: Scholten HJ, van Manen N, v.d. Velde R. editors. *Geospatial technology and the role of location in science*. Dordrecht, Springer; 2009, p. 15-29.

[18] Golledge RG, Marsh M, Battersby S. Matching geospatial concepts with geographic educational needs. *Geographical Research* 2008; **46**(1):85-98.

[19] Lee J, Bednarz RS. Components of spatial thinking: evidence from a spatial thinking ability test. *Journal of Geography* forthcoming.

[20] Just MA, Carpenter PA. Cognitive coordinate systems: accounts of mental rotation and individual differences in spatial ability. *Psychological Review* 1985; **92**, 137-72.