Assessing College Students' Spatial Concept Knowledge in Complexity Levels

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Abstract

This study probes undergraduate students' spatial concept knowledge and their comprehension. The researcher scored undergraduate students’ concept maps by evaluating the quality of interrelationships between concept nodes. The results of statistical analyses indicate that map scores are significantly different between the three complexity levels of spatial concepts, and the hierarchy of students’ comprehension matches Golledge’s ontological lexicon. These results imply that the scores of concept maps decrease as the complexity of spatial concept increases.

Keywords: spatial thinking, spatial concepts, concept lexicon, concept maps, GIS education;

1. Introduction

Since its introduction and utilization by limited groups of researchers, GIS has expanded to include a vast number and variety of users. The improvement of data availability, software and hardware usability, and geospatial technology accessibility now attracts users and enables them to solve spatial problems, increasing decision-making power in numerous disciplines and applications. In response, GIS education has also expanded from limited users and institutions to diverse disciplines and ages. The expansion can be characterized as a move from teaching about GIS for professional development to teaching with GIS as part of general public education. Unlike professional development students, a target group within public education programs consists of students who do not necessarily plan on using GIS for their occupations but rather to enrich their lives through the use of spatial technologies. In public education, GIS is regarded...
as a tool to reinforce students’ spatial thinking proficiency for real-life situations. The ultimate goal is to educate students to become good decision makers able to utilize geospatial technology wisely [1-4].

Scholars aware of the benefits of spatial thinking advocate spatial thinking education through GIS and believe it should be promoted [5-6]. GIS is considered an effective tool for nurturing students’ spatial thinking competency. Considering that tenet, enhancing spatial thinking in GIS education is an issue not only within spatial science disciplines but also throughout higher-education institutions. Therefore, for higher-education, GIS courses emphasizing spatial thinking should be established on a balanced mixture of geospatial technologies and knowledge and skills related to spatial thinking [5].

To the detriment of public education, there is little empirical research on college students’ understanding and knowledge of spatial concepts—the basis of spatial thinking—in relation to geospatial science [7]. Golledge [8] developed a conceptual framework of spatial ontology based on the complexity of spatial concepts. He and his students [9-11] mainly examined K-12 students’ knowledge and skills related to the spatial concepts integrated within the ontology. By applying Golledge’s thinking and methods, this current study explores college students’ comprehension of spatial concepts with the aim of ultimately determining which spatial concepts are easy or hard for undergraduate university students who enrolled in an introductory-level GIS course to understand. Evidence obtained from this empirical study could potentially suggest optimal and balanced use of geospatial technologies and spatial concepts in GIS education.

2. Literature Review

2.1. Concepts

Concepts are the labels of objects or events [12-13] that are abstracted through mentally generalizing and discriminating instances based on similarity and dissimilarity. Therefore, instances categorized into the same concept share common characteristics and attributes [14-15]. Moreover, labeled concepts are denoted by a socially accepted sign or symbols including a word or words [16]. The socially standardized characteristics of concepts are usually assigned by experts and authorities and stated in dictionaries and lexica [16]. These characteristics enable individuals to mentally distinguish examples from the non-examples within a category [16], utilize concepts for problem solving, and communicate with one another [14, 17-18].

The cognitive structure of conceptual knowledge is hypothetically represented with a hierarchical network [19]. The components of this hierarchical network are a concept node, a link, and a statement. A concept node, representing a concept, accompanies statements that explain a particular concept. In addition, a concept node is linked with other concept nodes. Concept nodes are structured hierarchically and can be categorized into superordinate and subordinate concepts. Superordinate concepts are positioned at the high levels of a hierarchical structure and include more general attribute information than subordinate concepts (e.g., an animal can move around by itself). Subordinate concepts are subsumed by superordinate concepts at the low levels. Subordinate concepts inherit their attribute properties from the superordinate concepts (e.g., a bird can move around by itself) and also have original attribute properties (e.g., a bird has wings). As a consequence, subordinate concepts positioned at the lowest level include the least general and the most specific attribute properties among the concepts embedded in a hierarchical structure (e.g., a penguin can move around, has wings, and can swim) [19].

2.2. Concept Maps

Since Novak devised the concept map [13], educators have used it to assess students’ current understandings, misconceptions, and knowledge development in various disciplines. For example, some researchers utilize the concept map to track student’s conceptual development and examine their
understandings in biology [20-23], chemistry [24-26], physics [27], medical science [28], and statistics [29]. Assessment using concept maps has mainly been practiced in the sciences; however, concept maps can also be used in pedagogy [30-31] and humanities such as history [32]. Some researchers reported the use of concept maps in geography [33-34]; however, there is no case study in GIS courses that extensively use spatial concepts.

A concept map is a semantic network form composed of multiple propositions. Each proposition includes two-concept nodes linked with a labeled link [13] and states the attribute of a concept [35]. A propositional statement ends with another concept node; thus, every concept is defined by a set of other concepts. A set of propositions is usually hierarchically structured and describes regularities and facts about a primary concept, which is usually positioned at the apex of a concept map. The concept nodes that link to a primary concept are the first-level concepts that subsume lower-level concepts at the subordinate position. Lower-level concepts inherit the attribute information from their superordinate concepts. The process of constructing a concept map involves recalling important concepts, contemplating interrelationships among those concepts, arranging those concepts, and explicating the attributes of those concepts [36]. As a consequence, concept maps externalize the important aspects of people’s cognitive structures [37-39]. Concept maps composed of multiple propositional statements enable assessors to infer what students know about a primary concept and how they relate other concepts.

As concept maps externalize structures composed of concepts and linking words [13] and interrelationships among concepts [35], concept map scoring scheme can be categorized into two types. One scoring scheme analyzes the hierarchical structures of the concept maps; the other scheme examines the quality of the interrelationships among concepts. The first scheme counts the number of map components and weighs map components closely related to a hierarchical structure [13, 40-42]. The second scheme examines the linguistic structures of propositions and explores the nature of interrelationships among concepts. The fundamental assumption is that a proposition is a minimum unit of the meaning that can be judged in terms of the validity of an interrelationship between two concepts [35]. A scoring weight for propositional statements is very high as compared with the first type of scoring schemes [29, 43]. Therefore, the second scheme is reconsidered an assessment of students’ knowledge by evaluating if their understandings of concepts meet concepts covered in instruction [43-44].

The scoring scheme focusing on the quality of propositions has variations of detail scoring methods. Roberts [29] modified the structural scoring scheme by weighing the accuracy of propositions. Ruiz-Primo, Schultz, and Shavelson [35] used a matrix and a propositional inventory to score concept maps by focusing on the quality of propositions. Rye and Rubba [43] referred to expert maps in their concept map scoring. Anderson and Huang [45] examined whether a relational scoring scheme with an expert map is a feasible measurement for knowledge attained by reading texts. The latter three studies adopted master models such as a propositional inventory and an expert map. This enabled the researchers to examine the degree to which students’ understandings matched experts’ knowledge.

2.3. Geospatial Concepts

Spatial concepts are one of the elements of spatial thinking. When spatial thinking occurs, spatial concepts support spatial representations and spatial reasoning by functioning as a framework for identifying, describing and analyzing various spatial events and objects [6]. When it comes to GIS software and map use, spatial concepts, which are also called geospatial concepts [10], affect the quality of map use and interpretation [9, 46]. Converting information obtained from maps to conceptual information requires extensive use of a variety of geospatial concepts. Therefore, geospatial concepts support several types of mental activities such as interpreting encoded cartographic models with a bird’s-eye view [47], grasping spatial relationships in a single glance [48], abstracting geometric information by manipulation [49], and identifying the geographic information that is not explicitly shown on a map [47]. This wide range of usability makes geospatial concepts diverse. Some geospatial concepts are merely
simple and primitive; in contrast, some concepts are derivatives that stem from primitives. In terms of visibility, some concepts can easily be perceived; on the other hand, some concepts can be embodied only through people’s spatial representations and reasoning. For example, map readers identify the concept of association by comparing spatial distribution, pattern and relationships described on two or more maps.

Some researchers have discussed simple geospatial concepts and the more complicated concepts that can be derived from the simple concepts. Nystuen [50] introduced a basis that provides a minimum set of concepts necessary for geospatial analysis. Papageorgiou [51] reconsidered Nystuen’s basis by emphasizing mathematically logical structure of spatial system and regarded the basis as a collection of primitives. Kaufman [46] examined the simple geospatial concepts that assist prospective teachers’ spatial analysis. He identified the simple concepts by paying attention to observable and measurable spatial relationships. Golledge [8] reconsidered the primitives introduced by Nystuen and Papageorgiou and established a geospatial concept lexicon and ontology based upon the complexity of geospatial concepts. According to him, there are primitives and four levels of derivatives [10]. The first-order derivatives, which are the simplest derivatives, include arrangements, distribution, direction, distance, and shape; the second-order derivatives feature adjacency, angle, coordinate, and polygon; buffer, connectivity, gradient, profile, representation, and scale are examples of third-order derivatives; the fourth-order derivatives are the most complex terms such as interpolation, map projection, and subjective space.

3. Experimental Design, Participants, and Domains

To probe individuals’ understandings of spatial concepts, this study adopted a single-group time series design as a part of a quasi-experimental design. The researcher conducted experiments in both the 2008 fall semester and the 2009 spring semester. In the experimental portion of this study, undergraduate students who enrolled in an introductory-level GIS course participated in a training session to learn how to create a concept map, followed by three experiment sessions in the beginning, middle, and end of each semester. In the three experiment sessions, participants constructed concept maps about space.

Seventeen undergraduate students of Texas A&M University voluntarily participated in this study. Of the seventeen participants, four withdrew from the study. In addition, a set of three concept maps drawn by a single participant was not hierarchically structured. As a result, the researcher analyzed thirty-six concept maps provided by twelve participants. Of the twelve participants, seven participants were students who enrolled in a course provided by the Department of Geography; the other five participants were students who enrolled in a course offered by the Department of Ecosystem Science and Management. Both courses concentrated on GIS basic skills and knowledge and the cartographic aspects of GIS in the first half of the semester. In the latter half of the semester, both courses gradually moved to topics about GIS analysis. A small number of subjects participated on a volunteer basis, implying that the sample may not be representative of all undergraduate students who attend a GIS course in U.S. universities. Results may not be generalizable. Considering these limitations, it can be said that the data and results of this study are not confirmatory, but rather suggestive and exploratory.

4. Methods and Analysis

The experiment of this study includes a training session and three experiment sessions. The goal of the training session is to learn about concept maps and creating a map by using concept mapping software, CmapTools [40]. The adopted contents and activities follow strategies introduced by Novak and Gowin [13]. Participants attend this session in either the researcher’s office or a university computer center. The duration of the session is roughly fifty minutes, during which each participant individually followed slides by themselves. The session has two parts. In the first part, participants learn the nature, roles, and elements of a concept map. In the second part, participants create two concept maps. For the first mapping, they create an Earth concept map composed of eighteen concepts by following step-by-step instructions.
After participants complete the first concept map, they construct a concept map about water by arranging eighteen concepts. During this, participants are not able to refer to any instructional material. At the end of the second mapping activity, participants check their maps to identify necessary revisions. The participants’ maps are then collected and examined to verify their validity and quality. As a result, it was confirmed that participants had appropriately attained concept mapping knowledge and skills.

In all three experiment sessions, participants draw a concept map of the presented primary concept—namely, space—using the concept mapping software. When participants open a concept mapping window to begin working, the page already includes thirty spatial concepts provided by the researcher. This setting is consistent across sessions. During mapping, participants are not required to use all thirty concepts; rather, they are invited to merely use the geospatial concepts with which they are most familiar. In addition, participants are advised during concept mapping to create a hierarchical form and to examine their finished map in order to identify parts requiring improvement before submission.

For this study, geospatial concepts utilized in the three experiment sessions were chosen based on two rationales; first, that adopted geospatial concepts should be covered in introductory-level GIS courses; second, that the concept collection should engage a diversity of spatially mental activities such as aerial perception, spatial relationship representations, geometric manipulation, and spatial reasoning. The following concepts were adopted: location, point, arrangements, distribution, line, shape, boundary, distance, size, spatial relationship, linkage, two dimensions, three dimensions, coordinate, polygon, cluster, dispersion, direction, density, topology, proximity, pattern, buffer, scale, distortion, association, map projection, network, diffusion, and overlay.

Over the course of the three experiment sessions, twelve participants satisfactorily created spatial concept maps. Their concept maps were then collected and scored by adopting the relational scheme, which focuses on the correctness of the propositional statements aiming to reflect students’ understanding of concepts covered in instruction [29, 35, 43-44]. For the relational scoring, this study adopted a combination propositional matrix and propositional inventory. The propositional matrix listed 435 possible pairs composed of the thirty geospatial concepts used in the experiment sessions. Each pair belonged to either a correct, partially correct, or incorrect category. For pairs classified as correct, the researcher formulated potential propositional statements.

In order to develop the matrix and inventory, the researcher listed the definitions of the thirty geospatial concepts by referring to DeMers’ [52] GIS introductory-level textbook, Witthuhn et al.’s [53] geospatial concept book, and a GIS dictionary on the website of ESRI, a leading GIS software vendor. The definitions extracted from the materials reflected experts’ thoughts and opinions. For example, the definition of cluster offered by DeMers [52] was as follows: “cluster demonstrates a type of distribution with a high density of features.” Once obtained, the definitions were examined to identify the pairs belonging to the correct category. In the case of “cluster,” the terms of “cluster” and “distribution” and “cluster” and “density” were pairs that fell within the correct category as the terms were specifically included in the definition of “cluster.” In the next step, the correct propositional statements were formulated by referring to the definition statements and correct pairs. In the following example, the concept of “cluster” was formulated: 1) cluster demonstrates a high density; 2) cluster demonstrates a type of distribution; 3) density is a measure of cluster; and 4) distribution representing a convergent condition is cluster. Establishing correct pairs and correct propositional statements enabled each of the thirty spatial concepts to have one or more correct pairs and two or more correct propositional statements. The study also examined possible pairs and propositional statements that potentially did not belong to a correct category. For instance, the terms of “cluster” and “diffusion” may induce the following statement: “cluster is a result of diffusion;” Likewise, the relationship between “cluster” and “spatial relationship” may be expressed by the following statement: “cluster describes a spatial relationship.” These propositional statements are neither definitions extracted from the referred materials nor other overarching concepts; however, those statements are correct under certain circumstances. Thus, the combination of “cluster” and “diffusion” and the combination of “cluster” and “spatial relationship” can be regarded as partially correct.
pairs and partially correct statements. The researcher assigned such statements to the partially correct category. After the researcher identified the pairs that belong to correct and partially correct categories, he assigned the possible pairs that belonged to neither a correct category nor a partially correct category to an incorrect pair category.

To initiate scoring within the relational scheme, the researcher rewrote the propositional pairs and the statements described in each of the obtained concept maps into a matrix. He scored the pairs and statements based on the three categories of propositional pairs and statements. The score range of propositional pairs was 0 to 2 points. If a pair matched one of pairs of the correct category, the pair received 2 points; if a pair was regarded as a partially correct pair, the pair received 1 point; if a pair belonged to neither a correct pair nor a partially correct pair, the pair did not receive any points. The score range of propositional statements was 0 to 4 points. A correct statement received 4 points; a partially correct statement received 2 points; an incorrect statement and a link without a statement did not receive any points. A combination of pair scores and statement scores established nine different accuracy categories (Table 1). The range of the combined scores was 0 to 6 points. Thus, if a participant’s proposition aligned with the experts’ definition, the proposition received 6 points in total. The results showed the mean values of scores gradually increased throughout the three experiment sessions (Table 2).

This study’s initial aim was to identify which geospatial concepts were easy or hard for undergraduate university students to understand. To answer this question, the researcher calculated concept-based scores by referring to a propositional statement matrix used for the relational scoring. In this matrix, each propositional statement was classified as a correct, partially correct, or incorrect statement either. Each of the propositional statements written by participants had two concepts at either end of its statement. The researcher assigned 4 points to a concept that was identified as a correct propositional statement; 2 points to a concept that was included in a partially incorrect statement; and 0 points to a concept related to an incorrect statement. To infer the complexity level of the thirty geospatial concepts, the researcher categorized these obtained scores into the following five complexity levels: the primitive level, the simple level, the difficult level, the complicated level, and the complex level. These complexity levels were based on Golledge’s geospatial concept lexicon and ontology [10-11].

For an inferential statistics analysis of the concept-based scores, the researcher aggregated the five levels into the following three levels: the primitive and simple level, the difficult level, and the complicated and complex level. The researcher conducted the Kruskal–Wallis test, followed by the Mann–Whitney test to determine whether there existed a significant difference between the three levels.
complexity levels. In these statistical analyses, the researcher also tested—with a set of concept-based scores that excluded two outliers—the concept of coordinates and the concept of map projection.

5. Results and Discussion

Table 3 shows the concept-based scores of thirty geospatial concepts. The spatial concept with the highest student scores was shape (280 points). This concept belongs to the simple level. The concept with the lowest student score was overlay with 31 points. This concept is classified as the complex level. Meanwhile, there were two outliers. The first outlier was the concept of coordinate that fell within the difficult category; the second outlier was the concept of map projection that fell within the complicated and complex category. As to the mean and median values of the three aggregated levels, the primitive and simple level was the largest. The complicated and complex level held the smallest mean and median values among the three levels.

The first inferential statistics analysis was the Kruskal–Wallis test. This test had a three-group combination in the case of a full set of the thirty concepts (Table 4). The significance level of this test was set at 0.05. It appeared that the scores were significantly different between the three levels in both of the case of a full set of concepts (H(2) = 6.51, p = 0.039). The second inferential statistics analysis was the Mann–Whitney test. This test was used to confirm the results of the previous Kruskal–Wallis test. A Bonferroni correction was applied; all effects are reported at a 0.0167 level of significance. It appeared that the scores were significantly different in a comparison between the primitive and simple concept level and the complicated and complex concept level (U = -2.35, p = 0.016) (Table 5).

Considering the results of the statistical analyses, it can be said that, in general, college-level participants’ comprehension of geospatial concepts matched Golledge’s framework established on the complexity of geospatial concepts. The results implied that participants’ comprehension decreased as the complexity of a concept increased. This implication yielded two interpretations. The first interpretation is that a majority of the time college students fail to understand higher-order geospatial concepts compared to lower-order concepts. The second implication is that geospatial concepts can be classified on the basis of the degree of complexity. Although existing research [9-11] suggested that Golledge’s framework can be used in a K-12 system, it can also be used to identify which geospatial concepts are easy or hard for college students to understand.

The results implied that instructors may use concept maps to assess students’ conceptual knowledge. For example, instructors could have students construct concept maps twice at various intervals. This would enable instructors to compare a single student’s two maps and identify his or her advancements. If instructors note the differences of propositional statements connecting two concepts, they could assess the degree to which students understand concepts covered in instruction. Feedback obtained from students’ concept maps could be constructive to the improvement of both students’ learning and instructors’ teaching.

The results of this study have implications for teaching strategies as well. The implication is that instructors may present simpler concepts just before they teach more complicated concepts to effectively assist students in learning the concepts. For example, a buffer polygon naturally involves the lower-level concepts such as location, distance, proximity, shape, and area. Unlike the concept of buffer, the concepts of association, overlay and topology are not directly represented by physical objects. These intangible concepts can be conspicuous through spatial representations and reasoning with lower-level concepts. High-level concepts require some prerequisite concepts for students to learn. The ontology and the results of this study recommend that instructors confirm students are familiar with prerequisite simple concepts before introducing more complicated concepts.

In college-level GIS courses, instructors should effectively teach knowledge and skills of spatial thinking while teaching about GIS. However, introductory-level GIS courses tend to be techno-centered [54]. Many novices are more likely to treat a lab manual as a cook book and follow the directions without
Table 3. Complexity levels and concept-based scores

<table>
<thead>
<tr>
<th>Complexity Level</th>
<th>Concepts</th>
<th>Scores</th>
<th>Complexity Level</th>
<th>Concepts</th>
<th>Scores</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primitive</td>
<td>Location</td>
<td>227</td>
<td>Difficult</td>
<td>Diffusion</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>Point</td>
<td>155</td>
<td></td>
<td>Dispersion</td>
<td>88</td>
</tr>
<tr>
<td>Simple</td>
<td>Arrangements</td>
<td>59</td>
<td></td>
<td>Linkage</td>
<td>82</td>
</tr>
<tr>
<td></td>
<td>Boundary</td>
<td>106</td>
<td>Difficult</td>
<td>Pattern</td>
<td>107</td>
</tr>
<tr>
<td></td>
<td>Direction</td>
<td>73</td>
<td></td>
<td>Polygon</td>
<td>111</td>
</tr>
<tr>
<td></td>
<td>Distance</td>
<td>131</td>
<td></td>
<td>Three dimensions</td>
<td>109</td>
</tr>
<tr>
<td></td>
<td>Distribution</td>
<td>189</td>
<td></td>
<td>Two dimensions</td>
<td>180</td>
</tr>
<tr>
<td>Difficult</td>
<td>Line</td>
<td>158</td>
<td></td>
<td>Buffer</td>
<td>48</td>
</tr>
<tr>
<td></td>
<td>Proximity</td>
<td>76</td>
<td>Complicated</td>
<td>Network</td>
<td>64</td>
</tr>
<tr>
<td></td>
<td>Shape</td>
<td>280</td>
<td></td>
<td>Scale</td>
<td>88</td>
</tr>
<tr>
<td></td>
<td>Size</td>
<td>61</td>
<td></td>
<td>Association</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td>Spatial relationship</td>
<td>191</td>
<td></td>
<td>Distortion</td>
<td>76</td>
</tr>
<tr>
<td>Difficult</td>
<td>Cluster</td>
<td>50</td>
<td>Complex</td>
<td>Map projection</td>
<td>165</td>
</tr>
<tr>
<td></td>
<td>Coordinate</td>
<td>223</td>
<td></td>
<td>Overlay</td>
<td>31</td>
</tr>
<tr>
<td></td>
<td>Density</td>
<td>47</td>
<td></td>
<td>Topology</td>
<td>32</td>
</tr>
</tbody>
</table>

Table 4. Results of the Kruskal–Wallis test

<table>
<thead>
<tr>
<th>Combination of Spatial Concepts</th>
<th>$H$</th>
<th>$p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full Set of Thirty Spatial Concepts</td>
<td>6.51</td>
<td>0.039</td>
</tr>
</tbody>
</table>

Table 5. Result of the Mann–Whitney test

<table>
<thead>
<tr>
<th>Pair of Two Groups</th>
<th>$U$</th>
<th>$p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primitive &amp; Simple - Difficult</td>
<td>-1.25</td>
<td>0.228</td>
</tr>
<tr>
<td>Primitive &amp; Simple - Complicated &amp; Complex</td>
<td>-2.35</td>
<td>0.016</td>
</tr>
<tr>
<td>Difficult - Complicated &amp; Complex</td>
<td>-1.65</td>
<td>0.101</td>
</tr>
</tbody>
</table>

requiring students to think spatially or critically. As a consequence, some students may complete a GIS course without acquiring spatial skills such as interpreting maps, creating effective maps, building spatial hypotheses, and performing GIS modeling [55]. Worse yet, students’ attained GIS operational techniques would become obsolete in the near future. Considering the fact that processing and visualizing graphical information is one of fundamental thinking skills for workforce [56], it can be said that the development of teaching models and strategies in spatial thinking education is an urgent issue throughout higher-education institutions. In response, it is perhaps time to consider how to teach and assess spatial concept knowledge and spatial thinking skills in the context of formal GIS education.
References


