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The Role of GIS-Based Spatial Learning for Promoting Spatial Abilities and Spatial Thinking in Context

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Abstract

Research shows that psychometrically-assessed spatial abilities (*e.g.,* spatial visualization and spatial orientation) can be improved through training, and that some training yields improvements that are transferable to novel contexts and tasks (Uttal et al., 2013). While the training of these spatial abilities may be valuable for some forms of STEM (science, technology, engineering, mathematics) learning, the training of spatial skills alone may not be sufficient to promote the kinds of spatial thinking that will promote long-term growth in education. In addition to training spatial abilities, it may be beneficial to teach students higher-order spatial thinking skills. In this study, we tested the hypothesis that participation in a year-long Geographic Information Systems (GIS) course (the GeoSpatial Semester) would yield measurable improvements in both spatial abilities and higher-order spatial thinking. Our results provide preliminary evidence to support this claim. Students who completed the GeoSpatial Semester demonstrated some improvement in spatial ability and showed increased use of select spatial problem-solving strategies, specifically their intent to use different forms of spatial representations when solving novel problems. These results provide some support for the use of GIS as a spatial learning tool and suggest potential benefits for continuing to research the effects of geospatial technology as a means for promoting spatial abilities and teaching higher-order spatial thinking skills.

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Lastly: I dedicate this dissertation to my mom and dad, who said I could.

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Chapter I: Theoretical Review

Spatial ability is essential for many everyday activities, from navigating the streets of an unfamiliar city to building a desk using only complex visual instructions. Spatial abilities can be defined as a person's ability to search a visual field, perceive objects within that field, form mental representations of those objects, and mentally manipulate those representations (Carroll, 1993). Importantly, spatial ability also involves the perception and comparison of relational structure(s) among objects (Ash, Duke, & Kerski, 2010; Bednarz, Acheson, & Bednarz, 2006; Gattis, 2004; Gentner, 1983; Kim & Bednarz, 2013; Newcombe, 2010; National Research Council, 2006; Uttal & Cohen, 2012; Wai, Lubinski, & Benbow, 2009).

The Organization of Spatial Abilities

Is there more than one kind of spatial ability? There are over 100 tests of spatial ability, and there is little consensus on what they measure or how they are organized (Uttal et al., 2013). Still, a variety of attempts have been made to organize and categorize types of spatial skills. For the purposes of this dissertation, I will focus primarily on three broad categories of spatial skills highlighted in Linn and Petersen's (1985) meta-analysis:

(1) spatial perception, or the determination of the position of objects with respect to one's own physical orientation, often in spite of distracting perceptual information

(2) mental rotation, or the ability to mentally transform a representation of a two- or three-dimensional object

(3) spatial visualization, or the process of creating a mental image of spatial information and mentally transforming or manipulating it.

In particular, I focus on two of these abilities – mental rotation and spatial visualization - because they are very relevant to learning in science, technology, engineering and mathematics (STEM), (Hegarty & Sims, 1994; Novick & Hurley, 2001).

Spatial Abilities and STEM Achievement

Spatial abilities are particularly important for attainment and achievement in professions related to science, technology, engineering and mathematics (STEM), (Hsi, Linn, & Bell, 1997; Shea, Lubinski, & Benbow, 2001; Wai, Lubinksi, & Benbow, 2009; Webb, Lubinski, & Benbow, 2007), even when math and verbal abilities are taken into account (Wai et al., 2009). Because spatial skills are critical to everyday life and STEM education and achievement, it is not surprising that educators and researchers have renewed calls for understanding and enhancing spatial skills (Bednarz & Kemp, 2011; Charcharos, Kokla, & Tomai, 2016; Golbeck, 2005; Goodchild & Janelle, 2010; Kim, 2011; Kim & Bednarz, 2013; Kim & Bednarz, 2013a; Lee & Bednarz, 2009; Liben, 2006; Metoyer & Bednarz, 2017; National Research Council, 2006; Newcombe, 2006).

Teaching Spatial Thinking

The importance of spatial abilities in STEM raises the question of how spatial abilities can be improved. Researchers have investigated and tested ways to teach spatial abilities (e.g., training participants to use first player action video games, see Feng, Spence, & Pratt, 2007), administering course-based training to improve mental rotation skills, (see Sorby, 2009), but overall, how effective is such training for improving psychometrically-measured spatial skills? There is now strong evidence that spatial abilities are malleable; they can be improved with training, practice, and experience. In a recent meta-analysis, Uttal et al. (2013) reviewed over two hundred studies designed to test ways to train spatial abilities and found that, on average, spatial ability training and practice led to almost one half of a standard deviation in improvement in trained spatial abilities, which strongly suggests that spatial ability training can be effective for yielding improvement in spatial skills.

Although we know that training spatial abilities can lead to improvements on spatial test performance, it is less clear whether this training lead to the kinds of cognitive growth and understanding that is of critical importance to education (Stieff & Uttal, 2015). Primarily, this is a problem of transfer: Researchers have argued that the improvements that result from training spatial skills may be limited to situations in which the training and real-world contexts are closely aligned (Maccoby & Jacklin, 1974; Sims & Mayer, 2002), which is a problem because skilled spatial thinkers need to be able to apply their skills to a variety of real-world and academic contexts (National Research Council, 2006; Newcombe, 2010).

The potential lack of transfer from the training of specific spatial skills to educational contexts is not unique to spatial cognition. This question evokes a long-standing debate in cognitive psychology: Does training basic ("core") cognitive abilities improve educational outcomes? Results have often suggested that it does not. One example comes from research on the effects of improving working memory on a variety of educational measures: As complex problem-solving requires working memory, researchers have argued that improving working memory would naturally lead to improvements in problem solving skills and overall educational achievement (Chein & Morrison, 2010; Klingberg, 2010; Morrison & Chein, 2011). Yet, while evidence does suggest that working memory performance can be promoted through training, there is little evidence such training leads to improvement in educational outcomes (Harrison et al., 2013; Shipstead, Redick, Engle, 2012).

Given the problem of transfer in training "core" cognitive abilities like spatial ability and working memory, many educators and researchers have argued that focusing on training basic spatial abilities alone is not sufficient to produce the kinds of wide-spread changes that are needed for success in education and in STEM disciplines (e.g., Bednarz & Bednarz, 2008; Bednarz & Kemp, 2011; National Research Council, 2006; Newcombe, 2006). Instead, researchers and educators are now calling for a different way of learning spatial skills, based on the idea of *learning in context*, or learning based on a variety of experiences and in many settings to promote transfer of learning to new situations (Ferrara, Brown, & Campione, 1986; Sandoval & Bell, 2004).

In summary, research on the training of spatial thinking has shown that basic spatial skills are highly malleable, but, as is true in other domains of cognitive training, it is not clear whether the effects of this training will lead to improvements in learning in schools and other educational contexts. Here I discuss the approach of teaching spatial thinking in context in greater detail.

Another Approach: Spatial Thinking in Context

The issue of lack of transfer in the training of psychometrically-assessed spatial skills has led to increasing interest in teaching students to apply their spatial skills to solve STEM-related problems instead of simply training psychometrically-assessed spatial skills in isolation. This new approach extends beyond simply training specific spatial abilities by teaching students to think spatially as they address problems and situations and teaching them to frame problems as spatially-relevant and solvable by spatial means. Specifically, this form of spatial thinking, or *spatial thinking in context* (SIC), occurs when people frame a problem or situation in terms of space, use spatial language to describe and communicate aspects of the problem, imagine alternative visual representations of the problem, and use their spatial abilities discern patterns, recognize relationships, and use that information to select a solution or predict an outcome (National Research Council, 2006). Thus, SIC occurs when individuals draw on their psychometrically-measured spatial abilities and higher-order reasoning skills to address problems and real-world situations. To further explain the construct of SIC, I now turn to a discussion of some of its key characteristics.

Characteristics of Spatial Thinking in Context

In this dissertation, I studied two important characteristics of SIC that have been identified in literature on spatial thinking (Bednarz & Bednarz, 2008; Bednarz & Kemp, 2011; Charbonneau et al., 2009; Huynh & Sharpe, 2009; Kim & Bednarz, 2013, Kim & Bednarz, 2013a, Lee, 2006; Liben, 2006; National Research Council, 2006; Tate, Jarvis, & Moore, 2005). The first characteristic, developing and engaging in spatial habits of mind, involves extending and applying spatial thinking skills to real-world, everyday situations and problems. The second characteristic, spatially-based problem solving, occurs when a person understands that a given problem can be addressed by spatial means and understands potentially useful ways to apply spatial thinking to solving the problem. I will now review both characteristics individually and explain how they serve as important elements of SIC.

Characteristic #1: Spatial habits of mind. The first characteristic of SIC relates to the idea of a "habit of mind." Broadly speaking, the term "habit of mind" refers to habitual engagement in a specific set of cognitive skills, processes, or actions (Charbonneau et al., 2009; Costa, 2008; Cuoco, Goldenberg, & Mark, 1996). A *spatial habit of mind* is a habitual way of perceiving, thinking about, and acting upon the world through a spatial framework (Kim, 2011; Kim & Bednarz, 2013a; Liben, 2006; Liben & Downs, 2003; Liben, Kastens, & Stevenson, 2002; National Research Council, 2006). Examples of spatial habits of mind include using maps to navigate when traveling, describing patterns in traffic using spatial language (e.g., using terms like *cluster, arrangement, left, right,* etc.), creating a visual or physical representation to enrich one's understanding of a new idea (e.g., when reading a book about black holes one could visualize the motion of a black hole's gravitational pull on nearby objects). Spatial habits of mind refer to these sorts of everyday, habitual patterns of thinking and behaving in real-world environments. To better explain the nature of SIC as it applies to critical thinking and problem solving, I now turn to the second characteristic of SIC of interest in this study: spatially-based problem solving.

Characteristic #2: Spatially-based problem solving. The second key component of SIC is the ability to apply spatial thinking skills to solving novel problems. Here I have adopted a framework for understanding spatially-based problem solving as proposed by the National Research Council (NRC, 2006). In its report on spatial thinking (entitled *Learning to Think Spatially*), the Council proposed two key components of spatial thinking in context – specifically, two key spatial problem-solving skills: (1) practicing spatial thinking in an informed way, and (2) adopting a critical stance to spatial thinking. Table 1.1 shows these problem-solving skills and their descriptions.

NRC spatial problem-solving skill	Description
1. Practicing spatial thinking in an informed way	Having a broad and deep knowledge of spatial concepts and spatial representations, a command over spatial reasoning using a variety of spatial ways of thinking and acting, and possessing well-developed spatial capabilities for using supporting tools and technologies
2. Adopting a critical stance to spatial thinking	Having the capacity to evaluate the quality of spatial data based on its source and its likely accuracy and reliability; can use spatial data to construct, articulate, and defend a line of reasoning or point of view in solving problems and answering questions; and can evaluate the validity of arguments based on spatial information.

Table 1.1. The NRC's framework for spatial problem-solving to be used in the present study.

I have adopted the National Research Council's framework of spatial problem solving because it is grounded in research on spatial cognition and its components reflect elements of spatially-based problem solving that can be emphasized in educational contexts. I will describe this framework for spatial thinking in more detail when describing my coding scheme in Chapters II and III.

Teaching Spatial Thinking in Context

Many researchers argue that SIC skills should be explicitly taught at all levels of education and across a wide variety of STEM domains (Bednarz, 2007; Liben & Titus, 2012; National Research Council, 2006; Newcombe, 2010; Nielsen, Oberle, & Sugumaran, 2011). The National Research Council (2006) argued that teaching spatial thinking in context skills enriches students' understanding of STEM learning content, particularly math and science concepts. This is important because SIC skills are not obvious to all learners; even learners who are in the habit of thinking spatially may not do so when confronted with an unfamiliar problem in an unusual context (National Research Council, 2006). Yet based on its survey of K-12 educational curricula in the U.S., the National Research Council (2006) found that, in general, it was assumed in the curricula that students possessed the requisite spatial skills needed to understand the content, and little to no information was provided to educators regarding how to teach students spatial thinking skills (see also Baenninger & Newcombe, 1995; Baker & Piburn, 1997; Black, 2005; Liben, 2006; Liben & Titus, 2012; McCormack & Mason, 2001; Newcombe, 2006). The National Research Council (2006) concluded its report by urging researchers to investigate methods for formally and systematically teaching spatial thinking in context skills. One potentially effective and increasingly popular approach for doing so involves the use of geospatial technology in classrooms.

Geospatial Technology as a Tool for Spatial Thinking

Given the complexity and importance of teaching SIC skills, researchers and educators have utilized various forms of technology to promote the development of higher-level spatial thinking (Bednarz, 2007; Liben & Titus, 2012; Newcombe, 2010; Nielsen et al., 2011). Geospatial technologies (*e.g.,* Geographic Information Systems, Google Earth, remote sensing) are frequently used as an instructional tool for teaching SIC skills because they provide users with a variety of opportunities to engage with and utilize spatial information and spatial representations that can facilitate problem solving (Baker et al., 2014; Lee & Bednarz, 2009; Wiegand, 2003). For example, the use of geospatial technologies provides users with multiple ways to visualize and analyze spatial information, thereby enabling them to analyze numerous paths to a solution (Bodzin, 2008; Bodzin & Anastasio, 2006; Hall-Wallace & McAullife, 2002). This affordance of geospatial technology-based instruction provides a unique advantage to studying its effects on both psychometrically-measured spatial abilities and SIC, mainly because the use of geospatial technologies may simultaneously promote both spatially-based problem solving and psychometrically-measured spatial abilities. In particular, Geographic Information

Systems (GIS) software has been frequently used in research on geospatial technologies and spatial thinking and is the technology used in the present study.

Geographic Information Systems (GIS)

GIS is a software package that allows users to view, analyze, and manipulate spatial information, thereby facilitating the creation and manipulation of digital spatial representations. GIS functions by representing geographic information or events in terms of coordinates (e.g., latitude, longitude, elevation) and points in time. GIS allows users to generate and manipulate multiple forms of spatial representations with which they can visualize and analyze several layers of spatial data. The ability to manipulate representations of spatial data with GIS facilitates spatial problem solving, as users can search for patterns or trends in data, make predictions based on those patterns, and represent their predictions or problem solutions by using spatial representation features of GIS.

GIS as a tool for spatial thinking: real-world example. To illustrate how GIS may be used in an educational setting to teach spatial thinking, I present the following example of a student's final project after a year-long course in GIS (with a focus on spatially-based problem-solving). This student sought to address a real-world problem for her project: the issue of determining a new restaurant's success in a new community. To predict an optimal location for a new restaurant to thrive in her hometown, the student used GIS to represent several forms of spatial data. First, to determine where potential restaurant customers would be likely to drive, the student created a map of cities within a 15-minute drive zone from her hometown (in clockwise order from the top left of Figure 1.1 - see the first image), which allowed her to identify areas where the restaurant would be in close proximity to attract the most customers. The second image shows the student's mapping of age information in the community. The third image shows the income for the surrounding community, and the fourth image displays population change data, which suggests that the area surrounding the restaurant's potential location will continue to grow. Based on the student's analysis and mapping of the data displayed in the four maps, she chose a restaurant location that would be most profitable for her business and practical for potential customers.

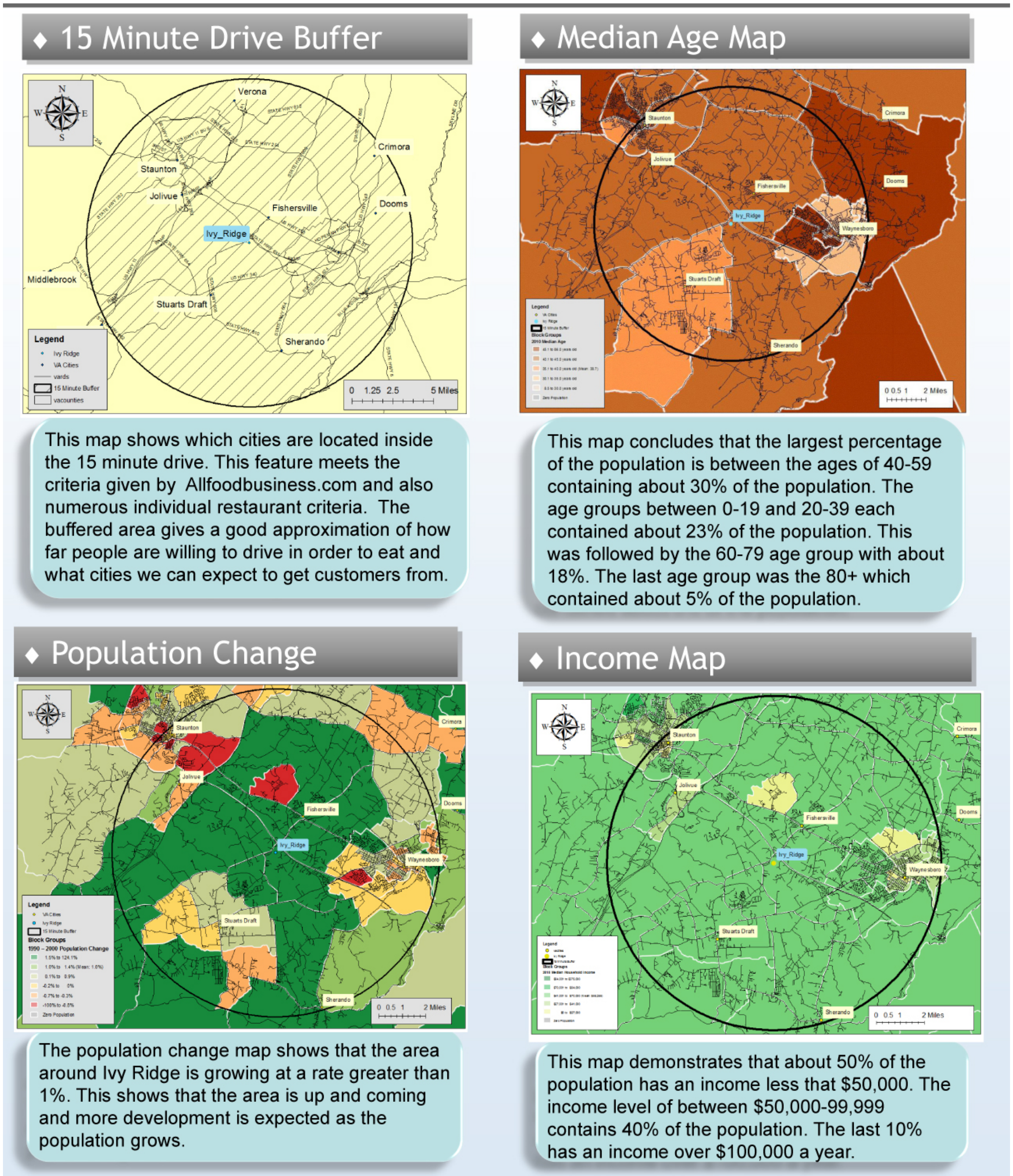

Figure 1.1 A student's poster of her final project in which she used GIS to determine an optimal location for a new restaurant in her local community.

Spatial Thinking in Context, Spatial Abilities and GIS-Based Spatial Learning

Many researchers have argued that there are benefits of GIS-based learning for promoting spatial thinking in context (Albert & Golledge, 1999; Bednarz & Bednarz, 2008; Hall-Wallace & McAuliffe, 2002; Huynh & Sharpe, 2009; Kerski, 2003; Kim, 2011; Kim & Bednarz, 2013; Kim & Bednarz, 2013a; Lee & Bednarz, 2009; Liu & Zhu, 2008; Liu et al., 2010; Milson & Curtis, 2009; Self, Gopal, Golledge, & Fenstermaker, 1992; Tate, Jarvis, & Moore, 2005). In the following section I review and critique arguments regarding this claim.

Does GIS-Based Learning Lead to Improvements in Spatial Thinking in Context?

Many researchers have addressed variations of this questions before (see Albert & Golledge, 1996; Bednarz & Bednarz, 2008; Bodzin, 2011; Bodzin et al., 2014; Hall-Wallace & McAuliffe, 2002; Huynh & Sharpe, 2009; Kerski, 2003; Kim, 2011; Kim & Bednarz, 2013; Kim & Bednarz, 2013a; Kolvoord, Uttal, Meadow. 2011; Kolvoord, Charles, & Purcell, 2013; Lee, 2005; Lee & Bednarz, 2009; Liu et al., 2010; Liu & Zhu, 2008; Milson & Curtis, 2009; Patterson, Reeve, & Page, 2003; Perkins, Hazelton, Erickson, & Allan, 2010; Shin, 2006; Tate, Jarvis, & Moore, 2005; Viehrig, 2014; Wigglesviorth, 2003). However, the interpretation of some research results is constrained by researchers' choice of methods or measures, so while many studies report finding positive effects of GIS on spatial learning, these findings need to be evaluated with caution, particularly in the case of measures that were purportedly designed to test for elements of SIC. In some cases, measures that were designed to measure aspects of spatial thinking actually also served as measures of content knowledge (e.g., in the case of a GIS-based geography course), or assessments of GIS-based skills. As an example, Kim and Bednarz (2013) developed an interview-based critical thinking assessment to use as their measure of spatial thinking in a study of the effects of GIS-based learning for spatial thinking, but the measure that the authors used may have placed the control group at a disadvantage. Kim and Bednarz sought to evaluate what they called “critical spatial thinking”, or “…the reflective evaluation of reasoning processes while using spatial concepts and spatial representation” (p. 351). The interview questions were reportedly designed to probe participants’ spatial thinking - mainly their abilities to evaluate the reliability of spatial data, engage in spatial reasoning, and assess problem-solving validity. During pre- and post-test sessions, thirty-two students in three groups (one group of GIS students and two control groups) completed open-ended spatial reasoning problems independently, then were asked to explain their reasoning that led them to their solutions. Kim and Bednarz reported that their analyses of participants’ responses showed that, compared to the two control groups, the GIS group alone showed significant improvement in critical spatial thinking skills from pre- to post-test. Kim and Bednarz then concluded that participation in the GIS course led to an increase in students’ skills in assessing the reliability of data, engaging in spatial reasoning, and assessing problem-solving validity.

However, it is important to note that some aspects of the problem-solving assessment and interview may have favored the GIS group, as Kim and Bednarz’s measure of critical spatial thinking included questions that required knowledge and skills related to GIS, which could have provided the GIS group with an advantage over the control groups as the GIS group would be more likely to have knowledge of GIS. For example, in one of the three performance tasks (Question 2, p. 354, Kim & Bednarz, 2013), participants were asked to find the best location for a flood management facility by using information from three maps. The authors stated that success on this task required the ability to mentally overlay and dissolve maps, an ability that is fundamental to GIS-based learning and GIS use (Albert & Golledge, 1999). Although Kim and Bednarz included two different control groups (students enrolled in an economic geography course and a general education course), there is no indication that either control group learned to use GIS, and thus assessment questions that require explicit knowledge of GIS techniques may have biased the results in favor of the GIS group. Other studies also may also have this general characteristic; the post-test assessments may require knowledge that was covered in the intervention but not in the control group (e.g., Bodzin, 2011; Viehrig, 2014). Thus, it can be hard to tell whether the observed gains stem from general improvements in spatial thinking or from more specific increases in knowledge of GIS. One of the goals of the present research is to address this concern by developing measures of spatial thinking that could (a) assess general benefits from the GIS-based instruction, but (b) do not require specific knowledge of particular GIS techniques. In summary, there is a need to address the role of GIS-based spatial learning for promoting both psychometrically-assessed spatial abilities and spatial thinking in context using both psychometric measures and measures designed to assess spatial thinking in context that are not embedded in knowledge of GIS procedures or content.

Psychometrically-Measured Spatial Abilities and GIS-Based Spatial Learning

There is some evidence to suggest that training and practice with GIS can lead to improvement in psychometrically-measured spatial skills. For example, McAuliffe (2003) found that two days of training students in a physics class how to use two-dimensional and three-dimensional representations led to improvement on a different type of spatial task (reading topographic maps), but the implications of longer-term spatially-based training need further investigation. To that end, I am studying the effects of spatially-based instruction in a classroom setting throughout the academic year. Does participation in this type of long-term, GIS-based spatial learning lead to improvement in core spatial abilities?

Some researchers have argued that use of GIS leads to significant improvements in psychometrically-measured spatial abilities (Baker et al., 2014; Golledge & Stimson, 1997; Kastens & Ishikawa, 2006; Lee & Bednarz, 2009), but while there are some compelling arguments for why GIS-based learning might promote psychometrically-measured spatial abilities, to my knowledge, more evidence is needed to support this claim. For example, Lee and Bednarz (2009) argued that many routine functions performed in GIS are closely related to psychometrically-assessed spatial abilities. The act of visually manipulating GIS map features and performing transformations of maps (e.g., changing map scale) are both examples of activities that may support spatial visualization skills (Golledge & Stimson, 1997; also see Lee & Bednarz, 2009 p. 195 for a list of GIS-related skills and how they relate to psychometrically-measured spatial skills). Thus, there is reason to suspect that by providing users with the opportunity to learn how to visually represent and transform spatial representations, GIS use promotes psychometrically-measured spatial abilities (Andrienko et al., 2007; Baker & White, 2003; Baker et al, 2014; DeMers & Vincent, 2007; Harvey, 2008; Hearnshaw & Unwin, 1994). There is still a need for empirical support to demonstrate that there are effects of GIS-based learning on psychometrically-measured spatial abilities. Thus, I designed the present dissertation study to include psychometric spatial tests to measure participants' spatial abilities at the beginning and end of the study to test whether participation in a year-long GIS-based spatial learning course does indeed lead to changes in these spatial abilities. My results have the potential to shed light on any effects of GIS-based spatial learning for promoting psychometrically-measured spatial abilities.

This test for the potential impact of GIS-based spatial learning on psychometrically-measured spatial abilities addresses one piece of the puzzle. However, an additional key question for this dissertation concerns the degree to which core spatial abilities and SIC are related. In other words, do people who have high levels of spatial ability also tend to have high levels of SIC? I predict that this is the case because the underlying hypothesis of SIC is that it is based on an application of, or extension of, one's fundamental core spatial skills to a variety of spatially-related contexts, including real-world problem-solving. Why might performance on my specific measures of spatial ability be related to performance on the measures of SIC? As one example, the spatial habit of mind of *pattern recognition* (Kim & Bednarz, 2013a) involves the ability to identify patterns and spatial relations among objects and to extend or predict patterns based on visuospatial information. This skill may relate closely to the spatial ability of visualization, or the ability to create a mental representation of an object and internally manipulate it. Thus, it is possible that that there is an association between levels of spatial abilities and spatial habits of mind such that individuals who demonstrate higher levels of spatial abilities will also score higher on measures of SIC. Such a finding would provide support for the argument that there is a relation between SIC and psychometrically-measured spatial abilities.

Introduction Summary

The need for research on spatial thinking in context raises three compelling questions that served as the motivation for the present research. The purpose of this dissertation is to address these questions:

1. To what degree does participation in a GIS-based spatial learning course lead to significant improvements in spatial thinking in context (SIC)?

2. To what degree does participation in a GIS-based spatial learning course lead to significant improvements in psychometrically-measured spatial abilities?

3. What is the relation between psychometrically-measured spatial abilities and SIC?

Outline of Dissertation

The rest of this dissertation is organized as follows. In Chapter II, I discuss some of the challenges inherent to measuring SIC and address these challenges by describing the measures for use in this study. In Chapter III, I present this study's methods. In Chapter IV, I present my results, and in Chapter V, I interpret my findings and conclude by suggesting areas for future research.

Chapter II: Ways to Measure Spatial Thinking in Context

Constructs and measurement go hand-in-hand. Thus, the definition of constructs such as *spatial thinking in context* (SIC) are closely related to how these constructs are measured. Therefore, the goal of this chapter is to discuss an approach to measuring and assessing SIC. For each of the measures introduced below, I describe the prior research that serves as motivation for the measure's use and how the measure is intended to provide information to address my research questions.

The construct of SIC is difficult and complicated to measure because people think spatially in different ways (National Research Council, 2006). For this reason, I have employed three measures designed to test various aspects of participants' spatial thinking in context. However, I expected these three measures to converge, as they have been designed to measure aspects of the same construct. To test this assumption, I have tested for relations between all three measures of SIC.

Measures of Spatial Thinking in Context: Overview

My first measure of SIC is a paper-and-pencil survey called the Spatial Habits of Mind Inventory, or SHOMI, (Kim & Bednarz, 2013a), which has been designed to measure participants' everyday spatial thinking habits. The other two measures of SIC are designed to assess spatial thinking and spatially-based problem solving and are based on participants' verbal responses to interview questions - the second measure, which is an analysis of participants' spatial word choice in their interview responses, provides a broad, general sense of their level of spatial thinking, and is complemented by my third measure: a detailed coding of spatially-based problem-solving skills in participants' interview responses. Each measure has its unique strengths and weaknesses, which I discuss in detail below.

SIC Measure 1: The Spatial Habits of Mind Inventory

Many scholars have discussed the importance of a spatial habit of mind, but until recently, there was not a validated, reliable test instrument with which to examine and test for spatial habits of mind. Kim and Bednarz (2013a) developed a measure of key components of a spatial habit of mind. They identified five subcomponents of a spatial habit of mind: pattern recognition, spatial description, visualization, spatial concept use, and spatial tool use (see Table 2.1 for a summary of each component and sample items from the SHOMI). On the SHOMI, participants report the degree to which they engage in a behavior or habit by rating their level of agreement with statements.

The SHOMI has several strengths. Kim and Bednarz (2013a) evaluated this survey for validity and reliability with a sample of 168 undergraduates, and their factor analysis showed that the SHOMI had good construct validity and high internal validity. These findings support the use of the SHOMI as one reliable instrument of spatial habits of mind. However, the SHOMI is not without limitations. It is a self-report measure, which could mean that participants may under or over-report their spatial habits of mind. In addition, the SHOMI provides general information regarding participants' spatial habits of mind, but it does not address aspects of spatially-based problem solving and participants' use of spatial language. Therefore, I included two other measures of SIC that have been designed to converge with the SHOMI. The second measure of SIC is based on a review of participants' problem-solving interview responses for their use of spatial language, and the third measure involves coding participants' responses for evidence of participants' use of spatially-based problem-solving strategies.

Spatial Habit of Mind Subcomponents (SHOMI)

Spatial habit of mind subcomponent	Description	Sample SHOMI item
1. Pattern recognition	Engaging in pattern recognition by attempting to detect spatial patterns in everyday situations, describing spatial patterns, and forming predictions or explanations based on trends in spatial information	When I use maps to find a route, I tend to notice overall patterns in the road network.
2. Visualization	Creating one's own external visual spatial representations in order to enhance the understanding of spatial information or to convey spatial information to an audience	When a problem is given in written or verbal form, I try to transform it into visual or graphic representation.
3. Spatial description	Using spatial language to communicate spatial information to others in an everyday context (e.g., when explaining the concept of gerrymandering to a friend by using vocabulary related to the concept of population density ("compact," "disperse").	I tend to use spatial terms such as location, pattern, or diffusion to describe phenomena.
4. Spatial concept use	The habit of considering concepts related to external spatial representations (e.g., map-like: location, scale, perspective, projection) to enhance one's understanding of a real-world situation, as in when an artist paints a representation of an imaginary landscape by first considering aspects of scale, viewpoint, and direction in the intended spatial layout of her painting.	When trying to solve some types of problems, I tend to consider location and other spatial factors.
5. Spatial tool use	The habit of using spatial tools (e.g., GPS, maps, Geographic Information Systems) to assist in the navigation of physical environments and enhance the understanding of spatial data. A driver in a new city might use a paper map to help him find his way to a new landmark, or a pedestrian looking for the fastest walking route to work may use Google Maps to select an optimal path.	I like to use spatial tools such as maps, Google Earth, or GPS.

Table 2.1. Descriptions of Kim and Bednarz's (2013a) five subcomponents of a spatial habit of mind.

Using Participants' Interview Responses to Assess Spatial Thinking in Context

The next two measures are based on the semi-structured interview portion of each participant's session. In these interviews, participants were presented with novel, hypothetical problems and were asked to think aloud as they try to generate a solution to each problem. The next two measures are based on these interview responses.

SIC Measure 2: Examining Spatial Language Use

This measure of spatial thinking involves an analysis of participants' choice of spatially-related words in their responses to the hypothetical scenario questions. I used this approach to analyze participants' use of spatial language because evidence suggests that people's word choice corresponds to their behavior and beliefs (Holmes et al., 2007; Semin & Fiedler, 1988; Simmons, Chambless, & Gordon, 2008; Tausczik & Pennebaker, 2010). For example, Pennebaker and King (1999) found that college students' choice of emotion words predicted their scores on the five-factor personality scale. As one might predict, students' use of negative emotion words (e.g., *sad, unhappy,* etc.) predicted their level of neuroticism, and their use of positive emotion words (e.g., *happy, joyful,* etc.) predicted both extroversion and agreeableness. People's word choice has been also shown to reflect aspects of their internal dialogue (Oliver et al., 2008), their personality traits (Pennebaker & Stone, 2003), and their perceptions of other people (Semin & Fiedler, 1988). Based on these findings, I argue that spatial word use (particularly in the context of participants' explanations when solving novel problems) is a useful indicator of the degree to which participants are framing novel scenarios as "spatial" in nature or conceptualizing the problems as solvable by spatial means.

How is word choice analyzed quantitatively? To efficiently quantify people's word choice for use in research on personality factors, Pennebaker and colleagues (2001) built on previous textual analysis programs to create *Linguistic Inquiry and Word Count (LIWC*). LIWC uses provide the program with a thematic list (or "dictionary") containing a list of words related to specific psychological constructs, and LIWC searches through language samples and counts the number of words in the text that match those in the provided dictionary.

Analyzing word choice as a measure of spatial thinking: study example. There is empirical evidence to support the use of spatial word choice as a measure of spatial thinking. In their study concerning the impact of GIS-based spatial learning on spatial thinking, Jant, Uttal, and Kolvoord (under review) analyzed participants' use of spatial words as a way to measure changes in their spatial thinking. Jant and colleagues predicted that participants enrolled in a year-long GIS-based course would demonstrate an increase in their use of spatial language in their problem-solving explanations from pre- to post-test interviews (conducted before and after the GIS course), while students in the control condition (who did not participate in a GIS course) would not demonstrate significant change in their spatial language use over time. The results supported this prediction: Compared the control group, the GIS group showed a greater increase in their use of spatial language from pre- to post-test. Data obtained from an additional measure designed to evaluate participants' spatial problem-solving skills also showed that only the GIS group demonstrated improvement in spatial problem-solving skills from pre- to post-test. Jant et al. concluded that participants' use of spatial language indicated that they were thinking spatially about the hypothetical problems. This finding provides evidence to support the analysis of spatial word choice as a means for measuring engagement in spatial thinking, so for this dissertation, I analyzed participants' spatial word use from their Time 1 and Time 2 interviews. Given the findings of Jant et al., I predicted that the participants enrolled in our GIS course would show a significant increase in their use of spatial language over time, while students in our comparison group would not show significant change in their use of spatial language over time.

SIC Measure 3: Coding for Evidence of Spatial Thinking in Participants' Responses

While a quantitative analysis of participants' spatial word use provides an efficient way to gain insight into participants' spatial thinking, word-count based analyses do not capture nuances in meaning in response, as word-counting software cannot detect many important aspects of conversational context, such as irony, sarcasm, or other nuances in verbal expression (Pennebaker et al., 2003; Pennebaker & King, 1999). For this reason, I have complemented the LIWC coding by coding participants' responses for evidence of overarching themes and expression of key concepts (Chung & Pennebaker, 2007; Groom & Pennebaker, 2002; Tausczik & Pennebaker, 2010).

Development of the Coding Scheme

I used a form of coding that would allow me to identify and analyze aspects of participants' spatial thinking in context. Specifically, I analyzed and rated participants' use of spatially-based problem-solving strategies as they respond to the hypothetical scenario questions. I developed my coding scheme by consulting the National Research Council's report on spatial thinking entitled *Learning to Think Spatially* (2006), in which the Council identified two key themes in spatial thinking from their review of research on spatial cognition. Table 2.2 provides a summary of the two themes in spatial thinking that are relevant to the current investigation.

Themes in Spatial Thinking	Key Skills
Theme #1. Practicing spatial thinking in an informed way	Having a broad and deep knowledge of spatial concepts and spatial representations, a command over spatial reasoning using a variety of spatial ways of thinking and acting, and well-developed spatial capabilities for using supporting tools and technologies.
Theme #2. Adopting a critical stance to spatial thinking	Have the capacity to evaluate the quality of spatial data based on its source and its likely accuracy and reliability; can use spatial data to construct, articulate, and defend a line of reasoning or point of view in solving problems and answering questions; and can evaluate the validity of arguments based on spatial information.

Table 2.2. Elements of spatial thinking in context from the NRC's (2006) report on spatial thinking.

Based on these two themes, I identified two spatially-based problem-solving strategies that I looked for in participants' responses to the interview questions in which they described their plan for solving a novel real-world problem-solving scenario.

Spatially-based problem-solving strategies

The intent to use spatial tools and representations. I developed a way to code for the strategy of using spatial tools and technologies in spatially-based problem solving. Then, coders reviewed participants' responses to identify participants' use of spatial representations as part of their plan to address the scenario questions. Specifically, participants' responses were coded for evidence and justification of how they would use spatial representations in their problem solving process.

The intent to use spatial data. Coders also evaluated how participants considered collecting, analyzing, and using spatial data as they planned to address their scenario problems. I have focused on how participants planned to use spatial representations and spatial data not only because these strategies are relevant to GIS-based spatial learning, but because they are relevant to STEM education as well. For example, in the Next Generation Science Standards (NGSS), the National Research Council (2013) argued that learning when and how to use spatial representations in scientific investigations is critical for success in STEM learning. For example, in the Scientific and Engineering Practices in the NGSS framework, the use of spatial representations is pertinent to the scientific practices of Asking Questions and Defining Problems (Skill #1), Developing and Using Models (Skill #2), and Analyzing and Interpreting Data (Skill #4). Similarly, the National Research Council argued that learning how to think critically about using spatial data (*i.e.*, knowing what forms of data would provide the information needed to design a solution and how to obtain them, understanding how the data could be analyzed to yield useful results, etc.) is a key scientific skill that needs to be taught at all levels of K-12 STEM instruction.

In this chapter, I have explained the rationale and motivation for my three measures of SIC. All three measures provide valuable information regarding participants' spatial thinking: the SHOMI provides a general, reliable way to measure participants' spatial thinking habits as they occur in real-world settings, while an analysis of participants' use of spatial language complements the coding of their spatially-based problem solving based on their interview responses. In the Methods section (Chapter III), I will explain the procedures and methods used in this study and will provide detailed information concerning the implementation of my psychometric measures of spatial ability and my measures of SIC.

Chapter III: Methods

In this section I will explain the methods and procedures used in this study. I begin by explaining the study context and will then present the procedures and methods.

Study Context: The Geospatial Semester (GSS)

This study's sample was comprised of high school students enrolled in The Geospatial Semester (GSS) as well as comparison group students who were not enrolled in the GSS. The GSS is a dual enrollment program between James Madison University and select high schools in the Virginia suburbs of DC. Throughout the GSS, students use GIS as a problem-solving tool to generate solutions to real-world, spatially-related issues. The GSS is taught over two sequential semesters in the academic year. During the first semester, students learn to master features of GIS as they begin to identify and solve real-world problems. During the second semester, students continue to use their GIS knowledge and skills to investigate a problem of their own interest and to prepare a presentation at the end of the academic year. Throughout the course, instructors explicitly teach students how to utilize GIS as a spatial problem-solving tool.

Participants

Participants were seventy-six high school juniors and seniors who were recruited from urban and suburban districts in Northern Virginia ($M_{age} = 16.7$ years; 36 females, 40 males). The GSS group was comprised of thirty-five students (16 females, 19 males) who were enrolled in the GSS course at the time of the study. The comparison group was comprised of forty-one students (20 females, 21 males) who were not enrolled in GSS at the time of the study and had not taken the GSS course in the past.

Participant Selection

Recruitment. As a part of recruitment, experimenters visited several junior- and senior-level high school classrooms (including GSS classes and comparison group classes – e.g., Advanced Placement English) in participating schools and asked students to individually complete the tasks/questionnaires described below. In addition, students' Preliminary Scholastic Aptitude Test (PSAT) scores were obtained from their high school records for use as one measure of academic achievement. Students who were interested in participating in the study completed the following questionnaires (all in paper-and-pencil format):

- *A demographic information questionnaire.* Participants provided information regarding their age, race, gender, and familiarity with Geographic Information Systems (see Appendix A for the full questionnaire)

  The Spatial Habits of Mind Inventory (SHOMI). See Appendix B.

Participant Selection: Propensity Score Matching.

When determining the effects of an independent variable it is ideal to have an experimental design in which participants are randomly assigned to treatment and comparison conditions (Cook, Campbell, & Shadish, 2002). However, this is not always possible, and in the case of the current study, we could not randomly assign high school students to the GSS or comparison condition. With a lack of random assignment, there arises the concern that the outcomes of this study are attributable to self-selection factors. For this reason, we used Propensity Score Matching (PSM) to reduce potential bias from self-selection. PSM occurs when participants in a comparison group are matched to those in the treatment group based on the similarity of their PSM scores. A PSM score represents the probability that a given individual would be assigned to the treatment condition based their scores on selected covariates

(Rosenbaum & Rubin, 1983). In our study, we calculated propensity scores for all potential participants (GSS and comparison group) and prioritized recruiting comparison group students whose scores most closely matched those of GSS participants. Potential participants were matched based on the following covariates:

-Whether the student had previously taken any course with a GSS teacher

-Whether the student was white or non-white

-Paper-folding scores

-Math GPA

-Gender

The use of PSM in this study allowed us to focus on recruiting those potential comparison group students who most closely matched GSS participants on the dimensions above. Thus the two groups enrolled in the study (GSS and comparison group) have been matched to the best of our abilities in our efforts to reduce the effects of a quasi-experimental design on our study outcomes.

Study Procedure

Participants completed study activities in two different study sessions: (1) Time 1 and (2) Time 2.

Time 1 Session Procedure

At the start of the academic year, participants completed Time 1 activities in a one-on-one session with a trained experimenter either in a classroom in the participant's high school or in a laboratory room at Georgetown University. The average duration of participants' Time 1 sessions ranged from approximately 60 to 90 minutes. During Time 1 sessions, participants from both the GSS and comparison groups completed the Embedded Figures Test (EFT), the Mental Rotation Task (MRT), and the hypothetical scenario interviews.

Time 1 Session Activities

Embedded Figures Test (EFT). At the beginning of each Time 1 session, participants sat at a computer while the experimenter provided instructions for completing the EFT. The experimenter then asked the participant to complete a several practice trials while the experimenter observed. If the participant answered three or more practice trial questions incorrectly, they were asked to explain the task instructions to the experimenter before beginning the test trial portion of the task. The experimenter then left the testing room while the participant completed EFT test trials.

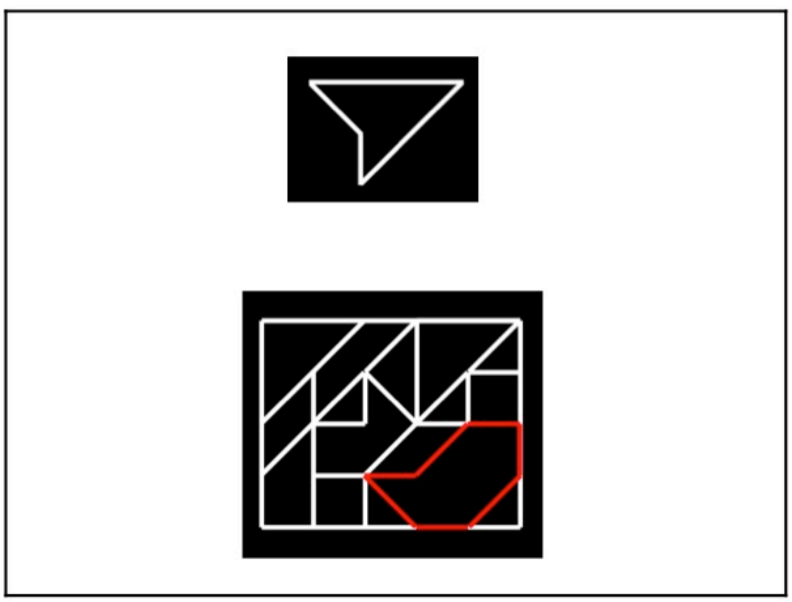

Figure 3.1. An example of an item from EFT. Participants need to determine whether the figure in white at the top of the screen is embedded in the figure on the bottom, despite the distractor figure (outlined in red on the bottom right).

Mental Rotation Test (MRT). Just as with the EFT, the experimenter asked the participant to complete a several practice trials while the experimenter observed. If the participant answered three or more practice trial questions incorrectly, they were asked to explain the task instructions to the experimenter before beginning the test trial portion of the task.

The MRT requires participants to decide whether a given figure is identical to a second figure. The two figures may be identical even if they are displayed in different orientations, so participants may mentally rotate one of the figures to try to align its orientation with other (Shepard & Metzler, 1971). See Figure 3.2 for an example item from the MRT.

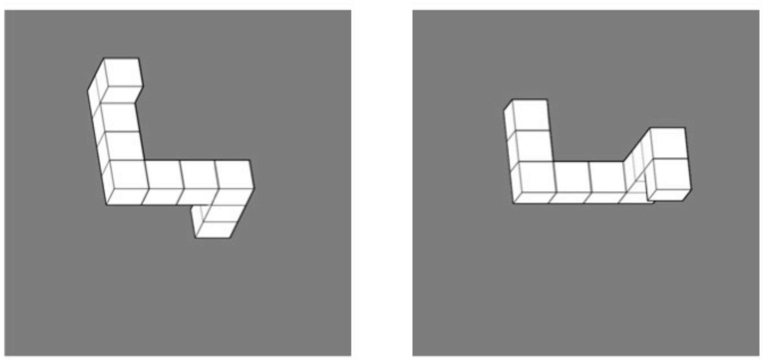

Figure 3.2. This is an MRT test item. Participants must determine whether the two figures pictured above are the same figure or if they are different figures. Participants often use a strategy of mentally rotating one of the figures to see if it is identical to the other (Shepard & Metzler, 1971).

Hypothetical scenario interviews. After the participant completed the EFT and MRT tasks, the experimenter initiated the hypothetical interview session by reading a question about a hypothetical problem-solving scenario then asked the participant to explain aloud how they would address the scenario problem (see Table 3.1 for a list of the hypothetical scenario questions). During the scenario interviews, participants were not provided with any information or resources with which to address the scenario problems, and the experimenter did not provide any additional information regarding the scenarios after reading the scripted questions. After the participant explained their proposed solution to the first scenario problem, the experimenter repeated this process for the remaining two scenario questions.

Hypothetical Problem-Solving Scenario Questions
Milk Prices "Why do you think milk prices differ from brand to brand? How would you predict what the price would be for each brand?"
Recycling Campaign "If you were running a campaign to increase recycling by your community, how would you go about running your campaign?"
Landfill "If your city needed to add an additional landfill and you were in charge of the process, how would you go about determining where it should be located?"
Gas Prices "Why do you think gas prices differ from station to station? How would you predict what the price would be for each station?"
Political Campaign "If you were running a campaign for a local political office, how would you go about running your campaign?"
Water Treatment Plant "If your city needed to add an additional water treatment plant and you were in charge of the process, how would you go about determining where it should be located?"

Table 3.1. The list of hypothetical scenario questions posed to participants in Time 1 and Time 2 interviews. During Time 1 interviews, participants were asked three of these questions, and at Time 2 they were asked the remaining three questions to ensure that no student received the same question twice. Question order was counterbalanced across conditions.

Time 2 Session Activities

Participants returned to complete Time 2 sessions at the end of the academic year. The procedure for the Time 2 session was identical to the Time 1 session: participants completed one-on-one Time 2 sessions with an experimenter either in a classroom at their school or at the laboratory at Georgetown University. Participants first completed the EFT and MRT tasks, followed by the hypothetical scenario interviews and then ended the session by completing the SHOMI a second time.

Methods: Coding

Qualitative Coding of Hypothetical Scenario Responses

In this section, I discuss in detail how participants' responses were coded for evidence of spatially-based problem solving in participants' responses to the hypothetical scenario questions. Specifically, participants' responses were coded their intent to use spatial representations and spatial data as they explained their solutions to the hypothetical problems. For the purposes of this dissertation, I use the term "spatial representation" to refer to any external (i.e., not mental) visual-spatial representation. Table 3.2 lists some examples of spatial representations that would be coded in participants' responses.

Examples of spatial representations for coding
Maps
Graphs/charts/plots
Static or interactive diagrams
Geospatial technologies (including but not limited to GIS, Google Maps, Google Earth)
3-D models
Sketches/drawings

Table 3.2. Examples of types of spatial representations to be counted in coding.

The term “spatial data” broadly refers to any data point that can be traced to a specific geographic location. Table 3.3 lists examples of types of spatial data that would be coded as forms of spatial data in this study.

General examples of spatial data use
Comparing U.S. Census population data by state
Comparing levels of job satisfaction by major metropolitan areas in the United States
Using the number of physicians per 1,000 citizens by country to predict health outcomes
Examining trends in CO_2 emissions by county by year
Analyzing political survey data as a way to predict the outcome of a local election
Estimating costs for various routes for shipping a product in order to find least costly route

Table 3.3. List of general examples of spatial data.

Spatial problem-solving strategies: Coding guidelines and rubrics. For all the interview responses, two coders reviewed each response and assigned a score for each of the two spatial problem-solving strategies (the intent to use spatial representations and the intent to use spatial data[1]). Scores for spatial thinking strategies ranged from 0 to 3, with a lower score representing a basic-level use of that strategy, and a higher score representing a more advanced use of the strategy. For each spatial problem-solving strategy, I review its scoring rubric and examples of coding below.

Spatial problem-solving strategy #1: The use of spatial representations. When coding for instances of participants’ use of this strategy, coders evaluated each response based on the criteria in the Spatial Representation Use Scoring Rubric (Table 3.4 below). Each score builds on the score below it. For example, a Level 2 score includes the criteria of a Level 1 score and the criteria for a Level 2 score, and so on. Participants’ responses were evaluated for evidence of

[1] For brevity’s sake, I refer to both spatial problem-solving strategies as “the use of spatial representations” and “the use of spatial data,” but note that, in our Time 1 and Time 2 interviews, participants did not have access to spatial data or spatial representations, so in reality participants are only expressing their *intent* to use spatial representations and spatial data.

both spatial representation use and spatial data use using the coding criteria in the rubrics for each strategy. These coding criteria were developed to reflect increasing levels of advanced use of the two spatial problem-solving strategies.

Rubric for Coding Spatial Representation Use

Score	Criteria
0	Participant does not express any intent to use any spatial representation
1	**Intends to use spatial representation as part of solution but does not justify why they are using it to generate a solution** *(Example: when answering the landfill question, a participant states that she would look at a map of the city but doesn't explain her reason for looking at a map as part of her problem-solving process*).
2	**Generally justifies use of spatial representation for scenario solution** Explains how/why that spatial representation will help them solve that problem *(Example: when answering the landfill question, a participant could mention that she would look at a map of the city to get a sense of where there might be available land)*
3	**Justifies use of spatial representation AND describes specific actions they would take to use it in problem-solving process** Describes at least one specific action they would take to use feature(s) of the spatial representation to solve the problem *(Example: when answering the landfill question, the participant says that she would use the scale feature on a map to help her estimate the distance between the original landfill and potential sites for the new landfill).*

Table 3.4. Rubric for scoring participants' scenario responses for evidence of intent to use spatial representation(s) in their problem-solving process

Spatial problem-solving strategy #2: The use of spatial data. When coding for instances of participants' use of spatial data, I evaluated each response based on the criteria in the Rubric for Coding Spatial Data Use (see Table 3.5). As with the scoring for the use of spatial representations, each score builds on the one below it.

Rubric for Coding Spatial Data Use

Score (points)	Criteria
0	**Does not express any intent to find or use spatial data for solving scenario problem**
1	**Intends to use spatial data but does not indicate how doing so would facilitate solving of scenario problem** *Example: When answering the recycling campaign question, a participant states that she would collect information about citizens' recycling habits by city.*
2	**Explains how general use of spatial data would facilitate finding a solution** *Example: when answering the recycling campaign question, a participant states that she would first find information about which neighborhoods produce the most recycling and speak with the residents in those areas about their good recycling habits.*
3	**Describes process of collecting, describing, reviewing and/or analyzing spatial data** Explains at least one specific step they would take with their spatial data in order to find solution to scenario problem *Example: When answering the recycling campaign question, a participant states that she would look at the percentages of people that purchase items that are recyclable, then examine those data by geographical area. Then, she would focus on promoting recycling in those areas first, then switch her efforts to areas where people purchase fewer recyclable items.*

Table 3.5. Rubric for scoring participants' scenario responses for evidence of intent to use spatial data in their problem-solving process.

Coding of Hypothetical Scenario Responses

Two raters coded a total of six hypothetical scenario responses from each participant (three responses from the participant's Time 1 interview and three responses from their Time 2 interview). Prior to coding, participants' responses were copied from their full interview transcripts and separated into individual files that were assigned random identity numbers to reduce potential for bias in coding of the same individual's responses to different scenario questions. Coders were blind to whether a response was provided at Time 1 or Time 2, the participant's condition (GSS or comparison) and gender. Coders used the scoring rubrics to assign each response a score. Coders' ratings of the responses were compared to assess inter-rater reliability.

Hypothetical Scenario Coding Examples

Here I discuss examples of participants' hypothetical scenario responses and explain how each response was coded for spatial representation use and spatial data use.

Coding Example 1

Participant Response	Coding score and justification
Question: If you were running a campaign to increase recycling in your community, how would you go about running your campaign? **Participant response:** "Well let's look at the percentages of people who purchase items that are recyclable in different areas. And target specific areas where certain areas are higher and we can try to recycle in those bigger targeted areas. And then that can trickle down into smaller areas and we can increase the amount of recyclables."	Spatial data use score: 3 Spatial representation use score: 0 This response received a score of 3 for spatial data use because the participant identifies a source of spatial data (the percentages of people who purchase recyclable items in given areas) and describes how she will use those data to focus her recycling campaign by first targeting areas where more recyclables are purchased. Since this participant does not mention using any kind of spatial representation, she receives a score of 0 for spatial representation use.

Coding Example 2

Participant Response	Coding score and justification
Question: If your city needed an additional water treatment plant and you were in charge of the process, how would you go about determining where it should be located? **Participant response:** "I would look at a map to see where the first water treatment plant is and see if there's any way to locate it like within the same region but I would also look at the layout of the city and see if there's any other appropriate places to see where the water plant could go so if you have a water plant here, you could maybe locate one over here so there's like an even distribution between plants and the city. And I think that's how I would go about doing that"	Spatial data use score: 0 Spatial representation use score: 3 This participant receives a score of 3 for spatial representation use because he explains that, in solving this problem, he would consult a map of the city in order to find the original water treatment plant location and use that information to decide where to locate the new water treatment plant. By using the map, he would be able to select a location for the new water plant that allows it to be close to the city but not too close to the original plant. The participant does not mention utilizing any sources of spatial data, so this response receives as score of 0 for spatial data use.

Coding Example 3

Participant Response	Coding score and justification
Question: Why do you think milk prices differ from brand to brand, and how would you predict what the price would be for each brand? **Participant response:** "I believe milk brands would be different in quality definitely, but also the ability of the company to get milk. And so I'd say that you'd find out which farm each milk company gets their supplies from and see into what factors affect that, for example if there's anything that's kind of abnormal for a given year with the milk, I'd say that prices would go higher because there's less product and there'd probably be more demand, or if there's more competition they'd lower the price to accommodate for that."	Spatial data use score: 0 Spatial representation use score: 0 While this participant considers the economic factors that influence the price of milk, she does not discuss any use of spatial data or spatial representation when explaining her reasoning about this question.

This concludes my discussion of the methods used in this study. In Chapter IV, I present my results.

Chapter IV: Results

In this chapter, I report the results of my analyses and discuss these results in the context of my three main questions concerning participation in GIS-based spatial learning and how it may impact spatial thinking. The first question was whether participation in the GSS might lead to significant improvements in spatial thinking in context (SIC). The second question was whether participation in the GSS might lead to significant improvements in psychometrically-assessed spatial abilities. The third and final question asked whether there might be a relation between levels of spatial ability and SIC.

I begin by reviewing my preliminary findings that showed significant differences in performance on some tasks by condition and sex. These findings are important to review because they may have an influence on the outcome of my final analyses. For example, I found sex differences in performance at Time 1. This was not surprising, as sex differences in performance on psychometric tests of spatial ability have been found frequently in the literature on spatial cognition (Fairweather & Butterworth, 1979; Grossi et al.,1979; Halpern & LeMay, 2000; Johnson & Meade, 1977; Kerns & Berenbaum, 1991; Linn & Petersen, 1985; Orsini et al., 1981; Vandenberg & Kuse, 1978; Voyer, Voyer, & Bryden, 1995). In my preliminary analyses, I also examined the possibility that performance on our measures could vary by condition. I will review the results of my preliminary analyses and then discuss the findings from my final analyses.

Results: Preliminary Analyses

For both of my EFT and MRT analyses, I analyzed participants' accuracy (or the proportion of correct responses out of the total number of trials) as well as their response time (in milliseconds). For the accuracy measures for EFT and MRT, scores represent the proportion of correct responses out of the total number of items, so on a scale from 0 – 1.0, thus a higher score represents better accuracy. Response times for EFT and MRT show the amount of time that elapsed from the start of the EFT or MRT trial until the participant responded. For each measure, I analyzed Time 1 performance by sex and condition. Table 4.1 displays a summary of the results for each analysis. The first column lists each measure, the second column reports whether there were significant differences in Time 1 performance on that measure by condition, and the third column reports whether there were significant differences in performance on the measure by sex.[2]

Measure	Significant difference in performance by condition?	Significant difference in performance by sex?
MRT accuracy	Yes, control group was more accurate	Yes, males scored higher than females
MRT response time	Yes, control group responded faster	No
EFT accuracy	Yes, control group was more accurate	Yes, males scored higher than females
EFT response time	No	No

Table 4.1. Summary of group differences at Time 1.

These results indicate the presence of some baseline differences by condition, as the comparison group outperformed the GSS group on MRT accuracy, MRT response time, and EFT accuracy. As the two groups did not differ in average PSAT score, GPA, or number of math and science courses taken, the superior performance of the comparison group was unexpected. One potential explanation for this is the self-selected nature of the study: Participants were not randomly assigned to either condition, so it is possible that there is something distinct about the GSS group that has to do with self-selection into the GSS course. Perhaps students were attracted to the GSS

[2] The full report of these results is included in Appendix C.

course because it seemed like it would offer them a chance to work more independently with spatial technology. Or, students who happened to self-select into the GSS did so because they were more interested in the project-based, hands-on nature of the GSS rather than other science courses offered by their schools that may focus less on inquiry-based learning. The final analyses for this dissertation took these Time 1 differences performance into account.

Results: Main Analyses

After completing my preliminary analyses, I revisited my three main research questions for this dissertation. I developed a set of analyses that would allow me to address each question. The analyses will be introduced as they relate to the three research questions.

Research Questions 1 and 2: To what degree does participation in spatially-based learning (GSS) lead to improvement in spatial ability and spatial thinking in context (SIC)?

To address these questions, I chose an analysis that would allow me to answer my key questions and address two important concerns. The first concern was the need to account for differences in performance on several of our measures at Time 1. The second concern was the need to understand the impact of participation in GSS on spatial abilities and SIC in conjunction (rather than analyzing performance on measures of each construct separately). I found an analysis that would eliminate the need to conduct a separate analysis for each individual measure (which would inflate the risk of Type I error). A multivariate analysis of covariance (MANCOVA) addresses both the issue of group differences at Time 1 and the need for a more comprehensive account of change in spatial ability and SIC over time. The MANCOVA accounted for group differences in performance at Time 1 because I included participants' Time 1 scores as covariates in the model (similar to how one would enter pre-test scores as covariates in an ANCOVA model when using it to analyze data from a repeated-measures design). The inclusion of the Time 1 scores as covariates in this MANCOVA model does not completely reduce the differences between the groups but it does remove some of the variance associated with the covariates from the overall error variance. This then leads to a smaller amount of overall error, which in turn yields a more powerful test of mean differences between groups (Tabachnick & Fidell, 2007). Thus, the MANCOVA analysis is suitable for my questions and my data because it allows me to account for some of the group differences at Time 1 and, in doing so, it provides a clearer sense of the differences between the groups' performance at Time 2.

Because a MANCOVA is able to analyze multiple dependent variables simultaneously, it provides an understanding of the effect of participation in the GSS on both SIC skills and spatial ability. The MANCOVA does this by creating a linear combination of all the dependent variables into one single dependent variable. The new dependent variable is adjusted for differences on the covariates, and then the model tests for the presence of statistically significant mean differences between groups (Tabachnick & Fidell, 2007). The result is a singular *p*-value that represents the overall effect of the independent variables on the combination of dependent variables[3]. Thus, with a MANCOVA model, I was able to determine whether participation in the GSS led to statistically significant improvement on measures of spatial ability and SIC without having to conduct a test for each dependent variable independently.

MANCOVA Results

The MANCOVA included data from all spatial ability measures (EFT accuracy and response time as well as MRT accuracy and response time) and data from two of the three measures of spatial thinking in context (LIWC and the SHOMI).[4] I included participants' Time 1

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[3] SPSS also provides the results of follow-up ANOVAs on each dependent variable. When there are significant effects for individual measures, I report the results of these follow-up tests.
[4] Data from the third measure of SIC (the spatially-based problem-solving questions) were ordinal in nature and not normally distributed, thus they were not eligible for inclusion in this model. I analyzed those data in a separate model which I will discuss after the results of this MANCOVA.

scores on all of the measures as covariates in the MANCOVA and added their Time 2 scores on the spatial ability and SIC measures as dependent variables. A 2 (condition: GSS, comparison) by 2 (gender: female, male) MANCOVA on participants' Time 2 scores revealed a significant overall effect of condition, $F(6, 61) = 3.32$, $p = .007$; $\eta_p^2 = .25$. There were no significant effects of gender or interaction between gender and condition, both *p*s > .05. Thus, when accounting for performance at Time 1, there is an overall effect of condition on performance on the measures at Time 2. Specifically, there was an effect of condition on participants' performance on EFT response time, MRT response time, and SHOMI. Since the effect of condition varied by measure, I will discuss the results for each individual measure.

Spatial Ability Results

EFT response time results. When controlling for performance on other spatial measures at Time 1, condition had a significant effect on EFT response time at Time 2, $F(1,66) = 5.41$, $p = .02$; $\eta_p^2 = .08$. At Time 1, the comparison group responded more quickly on EFT trials (M = 4614, SD = 1147) than the GSS group (M = 4718, SD = 1119), but at Time 2 the GSS group responded to EFT trials more quickly (M = 3788, SD = 1041) than the comparison group (M = 4023, SD = 1034). A comparison of the decrease in times for both groups revealed that the GSS group showed a greater decrease in response time over time than the comparison group (see Figure 4.1).

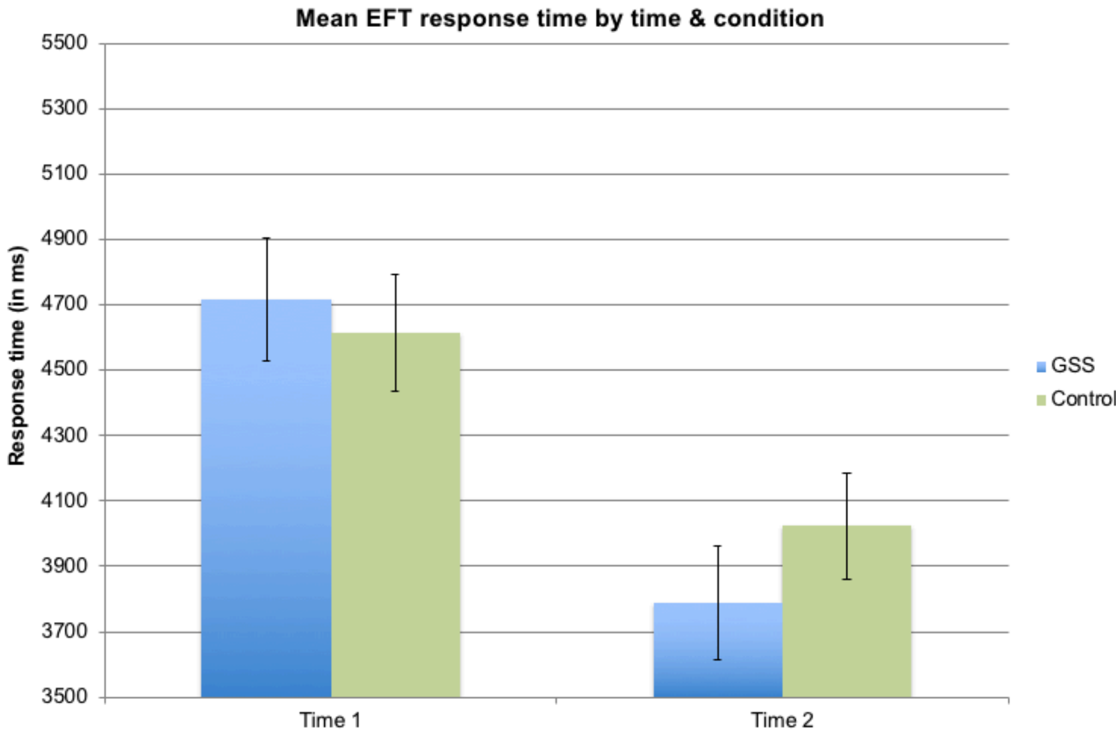

Figure 4.1. Mean response time on EFT trials by time and condition.

MRT response time results. When controlling for performance on spatial measures at Time 1, condition also had a significant effect on MRT response time, $F(1,66) = 4.95$, $p = .03$, $\eta_p^2 = .07$. At Time 1, the comparison group tended to respond more quickly to MRT trials (*M* = 3792, *SD* = 642) than the GSS group did (*M* = 4157, *SD* = 511). However, at Time 2, the GSS group responded, on average, just as rapidly (*M* = 3508, *SD* = 652) as the comparison group (*M* = 3545, *SD* = 579), see Figure 4.2.

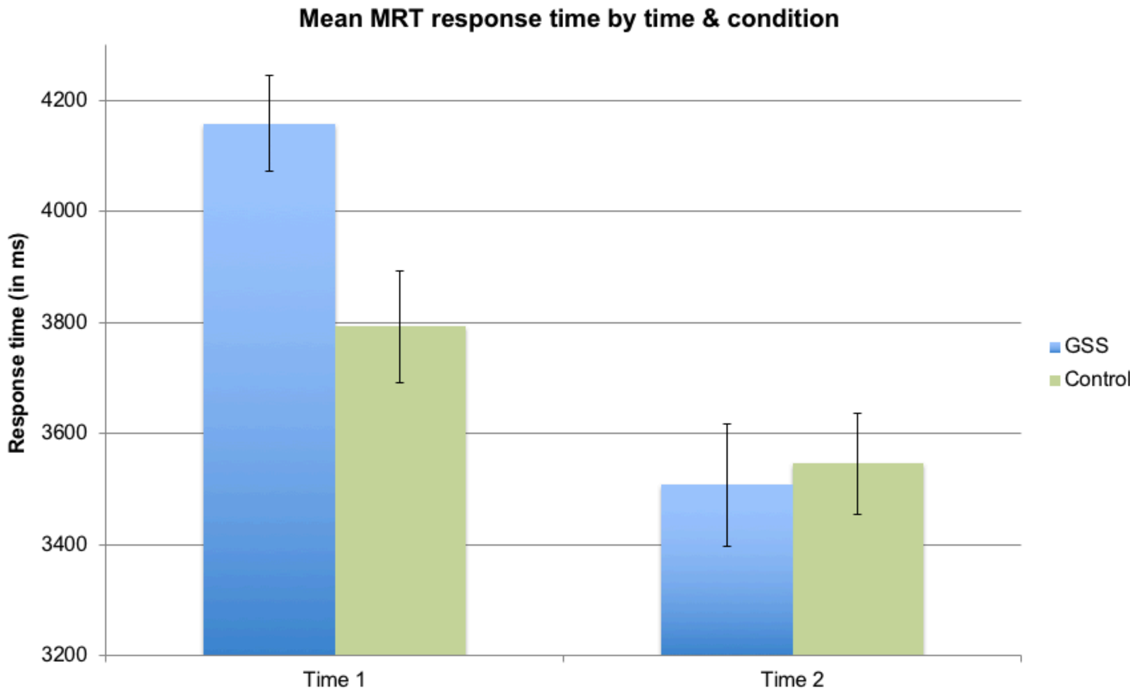

Figure 4.2. Mean response time on MRT trials by time and condition.

These EFT and MRT response time findings provide some evidence to address the question of whether participating in the GSS lead to changes in participants' spatial abilities. That is, while there was a significant effect of condition on EFT and MRT *response time*, I found no significant effect of condition on participants' accuracy on EFT and MRT trials in this analysis. I will address this finding more comprehensively in the general discussion section.

Spatial Thinking in Context Results

General SHOMI results.

The SHOMI is a 28-item questionnaire with a 5-point Likert-like scale. Thus, the participant rates each item on the SHOMI by selecting one of the following options:

(1) strongly disagree
(2) agree
(3) neutral
(4) agree
(5) strongly agree

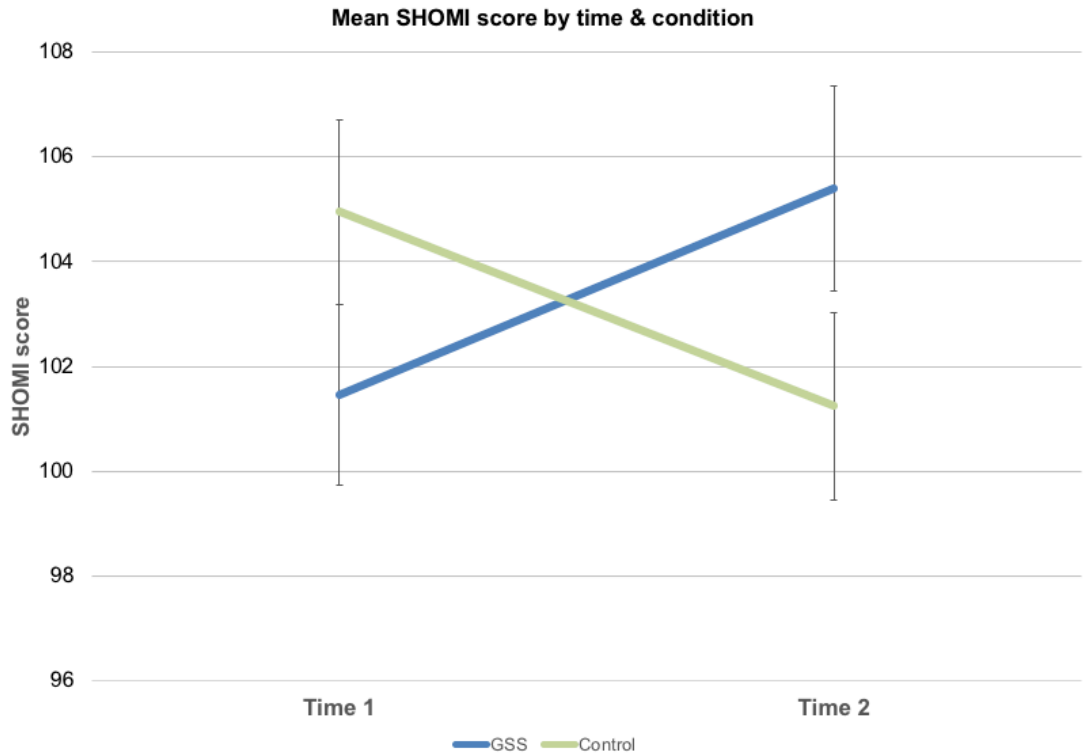

Figure 4.3. Mean SHOMI scores by time and condition.

Each item receives a score on the above scale of 1-5 with higher scores indicating more agreement with the statement, so that a response of "strongly disagree" would receive one point. Then, I calculated participants' average score for each of the five subcomponents (pattern recognition, visualization, spatial tool use, concept use, and spatial description) and an overall average score of all of their SHOMI responses. In all of my analyses, I used participants' overall average SHOMI scores (unless otherwise noted).

The MANCOVA revealed that there was an effect of condition on SHOMI scores, $F(1,66) = 7.78$, $p = .007$; $\eta_p^2 = .11$. Follow-up ANOVAs revealed that this finding may be explained in terms of a crossover effect. That is, while the GSS group showed a slight increase in

SHOMI scores from Time 1 to Time 2, the comparison group showed the opposite pattern (see Figure 4.3).

A paired t-test revealed that SHOMI scores for the GSS group increased significantly over time, $t(34) = -2.30$, $p = .03$. However, a second paired t-test revealed that SHOMI scores for the comparison group decreased significantly from Time 1 to Time 2, $t(40) = 2.34$, $p = .03$. The fact that the comparison group showed a decrease over time makes the process of comparing the two groups' performance more difficult. I will discuss the implications of this comparison in more detail in the discussion section.

MANCOVA null results. The rest of the MANCOVA results revealed no significant effect of condition or sex on EFT accuracy, MRT accuracy, or LIWC scores, all *p*s > .05. I will briefly discuss the potential explanations for these null results by measure.

EFT accuracy. The changes in EFT accuracy did not differ significantly by group (see Table 4.1 below for means and standard deviations for both groups at Time 1 and Time 2).

EFT accuracy	T1 group mean	T1 SD	T2 group mean	T2 SD	Change in mean score over time
GSS	0.64	0.19	0.68	0.11	+0.04
Comparison	0.69	0.15	0.66	0.17	-0.03

Table 4.2. Means and standard deviations for EFT accuracy for the GSS and comparison groups.

MRT accuracy. The changes in MRT accuracy did not differ significantly by group over time (see Table 4.2 for means and standard deviations for both groups at Time 1 and Time 2).

MRT accuracy	T1 group mean	T1 SD	T2 group mean	T2 SD	Change in mean score over time
GSS	0.74	0.13	0.82	0.13	+0.08
Comparison	0.79	0.13	0.87	0.12	+0.08

Table 4.3. Means and standard deviations for MRT accuracy for the GSS and comparison groups.

For both EFT and MRT accuracy, the GSS and comparison groups both made very similar change over time (an increase of .08 points in accuracy for both).

It is unclear why the GSS group showed a statistically significant level of improvement in response time on EFT and MRT but did not show a statistically significant improvement in accuracy on either of those measures (when compared the comparison group). One potential explanation for the GSS group's improvement in response time and lack of significant change (in relation to the comparison group) in accuracy is that the experience of participating in GSS may have led to a feeling of greater confidence when responding to items on spatial tasks like the EFT and MRT at Time 2 compared to Time 1. So, while participation in the GSS may not have led to better accuracy on EFT and MRT items over time, participation in such a spatially-based learning experience may have led to an increase in confidence or comfort with spatially-related questions.

Spatial word use (LIWC).

Participants' responses to the hypothetical scenario questions were transcribed and then analyzed using LIWC software. Before using LIWC, I searched each participants' Time 1 and Time 2 interview transcripts to identify uses of spatial words and removed spatial words that were used more than once. In addition, I eliminated spatial words that were used in a non-spatial manner. For example, if participant said, "That answers your question, right?" after giving their response to a scenario question, I would eliminate the word "right" from that question in the transcript because in that case, "right" is not being used as a spatial word. If, however, a participant said, "The park is to the right of the lake," then I would count the use of the word "right" as a spatial word. After eliminating spatial words used more than once and removing non-spatial uses of words, I used LIWC to obtain a raw count of each participant's use of spatial words. I provided LIWC with a list of spatial words, or a spatial “dictionary”, and LIWC searched through my transcripts to count the number of spatial words used from the dictionary. For my dictionary of spatially-related terms, I combined the spatial word dictionaries created by Pennebaker et al (2001) and Cannon, Levine, and Huttenlocher (2007), (see Appendix G for the full dictionary used in this study). To control for participants’ total talk time, I divided the number of spatial words used in their responses by the length of their response in minutes. Thus for my dependent variable for the LIWC analyses, I used the number of spatial words participants used per minute of their responses.

The results revealed no significant effect of condition or time on participants’ use of spatial language. This finding is puzzling because in Jant et al.’s study (in which they conducted pre- and post-test hypothetical scenario interviews that were similar to ours), they found that the GSS group (but not their control group) showed a greater increase in spatial words use in their interviews. We used the same interview questions as Jant et al., but we failed to find the same pattern in our results. Given that our experimenters read the same scenario question prompts as Jant et al., it seems unlikely that the differences between the studies’ results could be attributed to differences in the question topics or phrasing. It is possible that, in comparison to Jant et al.’s sample, that our sample gave shorter responses overall or simply tended to use fewer spatial words in general.

Effects of participation in GSS on spatially-based problem-solving

Because the coding scores for both spatial data and spatial representation use were ordinal in nature and non-normally distributed, they could not be analyzed in the MANCOVA model. To test for potential evidence of the impact of participation in the GSS on spatial problem-solving, I conducted a separate type of analysis for those coding scores. Because the data were non-normally distributed, I used a non-parametric adjusted rank transformed ANOVA (Leys & Schumann, 2010)[5] to test for the possibility of any effects of time and condition on use of these spatial problem-solving strategies.

Spatial problem-solving strategy use (spatial representation use and spatial data use) were coded and analyzed separately, so their results will be reported individually. Interrater reliability for the spatial data use and spatial representation use scores was assessed for two coders (including myself). When evaluating participants' use of spatial data, there was high agreement between the two coders' judgments, Cohen's weighted $\kappa = .880$ (95% CI, .851 to .910), $p < .0005$. When evaluating participants' use of spatial representations, there was moderately high agreement between the two coders' judgments, Cohen's weighted $\kappa = .703$ (95% CI, .461 to .945), $p < .0005$.

A repeated measures ANOVA on the spatial data use scores revealed no significant effect of time or condition, *p*s > .05. As shown in Table 4.4, both the GSS and comparison group's scores remained well below 1.0 for both time points.

Spatial data use	T1 group mean	T1 SD	T2 group mean	T2 SD
GSS	0.57	0.50	0.80	0.74
Comparison	0.67	0.50	0.71	0.57

Table 4.4. Spatial data use means and standard deviations for the GSS and comparison groups.

[5] "To conduct an adjusted rank transformed ANOVA, the raw data are adjusted by subtracting the respective marginal means from each observation. A rank is then assigned to each adjusted observation, and a classical factorial ANOVA is conducted on the adjusted ranked data. Main effects are subsequently calculated by subtracting the interaction from the raw data, ranking the adjusted observations, and then conducting a parametric test. Finally, simple effects are computed by reconstructing the sum of squares and error term" (Schumann, Zaki, & Dweck, 2014; p. 483)

Although there was some small change in the GSS group's score over time, it was not statistically significant. These null results will be discussed in more detail in the General Discussion in the context of my discussion of the spatial representation results.

For the use of spatial representations, a repeated measures ANOVA revealed a significant main effect of time and a significant interaction between time and condition, $F(1, 170) = 9.47$, $p = .002$, $\eta_p^2 = .07$ (see Figure 4.4). This result indicates that, in comparison to the comparison group, the GSS group showed a greater increase in their use of spatial representations when solving novel problems.

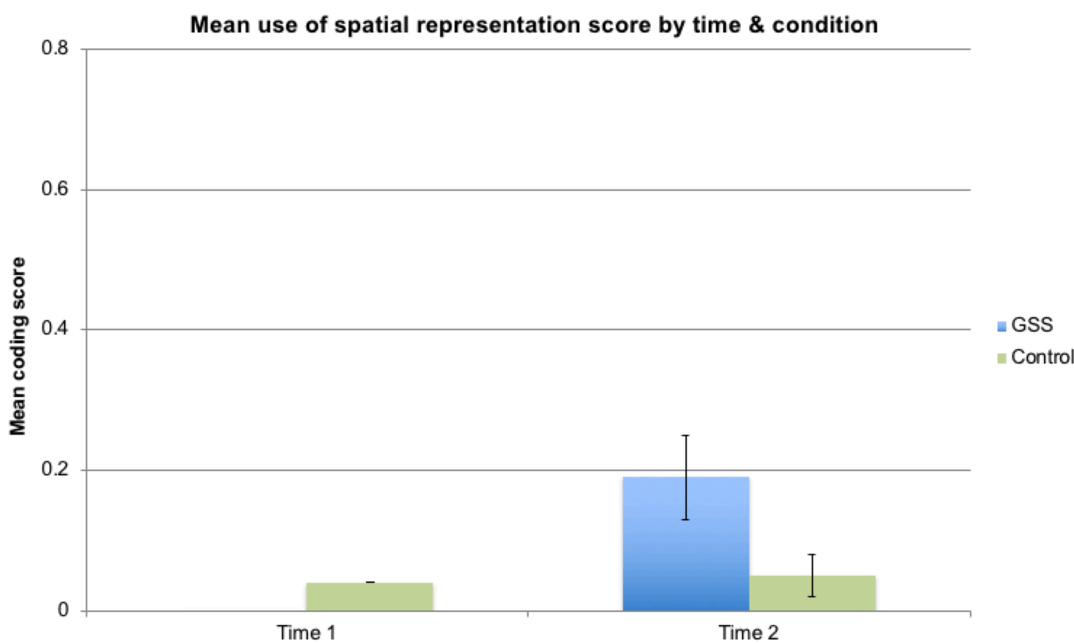

Figure 4.4. Mean use of spatial representation score by time and condition.

Question 3: To what degree are SIC and spatial abilities related?

My third question asked if there are relations between participants' levels of spatial ability and their levels of SIC skill. To address this question, I examined the correlations between participants' performance on the spatial ability measures (EFT and MRT accuracy and response time) and SIC measures (SHOMI, LIWC, and spatial problem-solving). Because my focus here was on correlations between SIC and spatial abilities, and not on the effects of GIS or spatial learning over time, I combined the data from both timepoints so that all Time 1 and Time 2 scores for each measure were included. Additionally, I examined the correlations between all of the SIC measures (SHOMI, LIWC, and spatial problem-solving) to assess the degree of convergence between the measures.

Correlation of Spatial Ability and SIC Measures

The results of this analysis reveal some preliminary evidence of a relation between spatial ability and SIC, as performance on some measures of SIC were significantly correlated with measures of spatial ability. I will review each significant correlation below (for tables showing the correlations for all the measures used in this dissertation, please see Appendixes D and E).

SHOMI and EFT and MRT. SHOMI scores were significantly correlated with EFT accuracy, $r(150) = .20$, $p = .01$, and MRT accuracy, $r(150) = .17$, $p = .04$. This finding indicates that higher scores on the SHOMI were associated with better EFT and MRT accuracy. One possible explanation for this is that some of the SHOMI items tapped into some of the same spatial abilities measured by the EFT and MRT. For example, some of the items in the SHOMI subcomponent of *pattern recognition* ask participants to report whether they notice patterns embedded in larger shapes or distributions, and the EFT is designed to test a similar skill, as participants are asked to visually search for select figures within larger ones. In addition, some of the SHOMI subdivision of *visualization* items measure participants' habits of creating and using internal and external visualizations to help them understand spatial information. For example, one SHOMI visualization item asks participants to rate their agreement with this statement: *When a problem is given in written or verbal form, I try to transform it into visual or graphic representation* (Kim & Bednarz, 2013a). Participants who habitually tend to internally visualize information in real life (especially if they tend to represent spatial aspects of a scene that are dynamic) may mentally rotate the stimuli in the MRT more readily. In this way, participants who report engaging in more spatial habits of mind may be engaging in spatial thinking practices in real life that also affect their psychometrically-tested spatial abilities.

SHOMI subcomponents and EFT and MRT. I also analyzed whether some specific subcomponents of the SHOMI were related to EFT and MRT. I computed participants' mean score for two of the subcomponents of the SHOMI: *pattern recognition* and *visualization.* To test whether participants' pattern recognition and visualization habits were related to their performance on the EFT and MRT, I conducted a series of correlations with participants' average pattern recognition and visualization scores and their EFT and MRT accuracy and response times. Results showed that higher scores on pattern recognition were moderately associated with higher accuracy on the MRT, $r(150) = .21$, $p = .008$. This finding suggests a relation between the habit of pattern recognition and higher levels of mental rotation skills. However, this correlation is quite modest, so this conclusion needs more support from further testing. The correlation results also revealed that participants who reported engaging in more pattern recognition on the SHOMI also tended to respond more quickly on EFT trials, $r(150) = -.18$, $p = .02$. Again, this finding could suggest that increased engagement in pattern recognition is associated with better spatial ability, but this correlation is also modest, and thus further research is required. Scores on the subcomponent of visualization did not correlate significantly with performance on any other measure.

Spatial problem-solving and EFT AND MRT. My results suggest that there may be a relation between spatial problem-solving and performance on two of our spatial ability tasks. Spatial data use scores were positively correlated with MRT accuracy, $r_s(148) = .25$, $p = .002$. In addition, spatial representation use scores were negatively correlated with response time on the EFT, $r_s(148) = -0.17$, $p = .03$ and MRT, $r_s(148) = -0.2$, $p = .013$, such that higher spatial representation use scores were associated with faster response times on both the EFT and MRT. These two findings may indicate that there is indeed a relation between SIC and spatial ability.

However, these correlations are not very strong, so it will be important to assess this question with other measures in the future.

In addition, before drawing the conclusion that there is a relation between SIC and spatial ability, it is important to rule out other possibilities. For example, it is possible that all these correlated measures are recruiting the same types of general cognitive abilities, such as general intelligence. Although I did not have access to measures of participants' general intelligence, I did have participants' PSAT scores, which are closely related to IQ (Frey & Detterman, 2004; Rohde & Thompson, 2007). PSAT was not significantly correlated with EFT and MRT accuracy nor response time, and PSAT was not significantly correlated with spatial data or spatial representation use scores, all *p*s > .05. Still, it is possible that other cognitive abilities (e.g., executive functioning) could play a role in participants' spatial learning, so further research will be needed to address this possibility.

Convergence of SIC Measures

The results of the MANCOVA analysis show that performance on some of the SIC measures was correlated with performance on other SIC measures. This is important to discuss because some of the SIC measures – especially the coding of participants' spatial problem-solving need to be validated with other measures of spatial thinking.

Spatial problem-solving and SHOMI. Spatial representation use scores were significantly correlated with participants' responses on the SHOMI, $r_S(148) = .19$, $p = .02$. The presence of this modest relationship is not surprising because, on the SHOMI, participants were asked about their use of spatial representations in real-world settings, and when participants' hypothetical scenario responses were coded according to the coding scheme, their responses were rated based on the degree to which they planned to utilize forms of spatial representations in their problem-solving process. So, this correlation likely indicates that participants who used spatial representations in real-world settings were more likely to use these representations when solving novel problems spatially.

Spatial problem-solving and spatial language use. Spatial data use scores were significantly correlated with participants' spatial word use, $r_s(148) = .20$, $p = .01$. It is possible that, during these hypothetical scenario interviews, participants who scored higher on spatial data use also tended to use a variety of spatial terms to explain how they would obtain and use their spatial data. For participants who described using a spatial representation to solve their scenario problem, they may have been able to explain their representation use with fewer spatial words.

In summary, the results from my correlation analyses suggest some consistency between measures of SIC – specifically, I found significant correlations between participants' spatial problem-solving (strategies of using spatial data and spatial representations) and their SHOMI scores and use of spatial language. It is important to note that the correlations discussed above are not very strong in nature, so before drawing the conclusion that these relationships exist, further research is needed.

Chapter V: General Discussion

Researchers of spatial cognition have frequently studied ways to promote psychometrically-assessed spatial abilities through practice and training (e.g., playing video games, practicing taking spatial tests). In some cases, this type of training has yielded significant growth in spatial abilities (Uttal et al., 2013a), but many researchers and educators have argued that the training of basic spatial abilities alone is not sufficient for promoting success in education. Researchers have argued for a more contextual approach to teaching spatial skills (Bednarz & Kemp, 2011; Charcharos, Kokla, & Tomai, 2016; Golbeck, 2005; Goodchild & Janelle, 2010; Kim, 2011; Kim & Bednarz, 2013; Kim & Bednarz, 2013a; Lee & Bednarz, 2009; Liben, 2006; Metoyer & Bednarz, 2017; National Research Council, 2006; Newcombe, 2006). That is, rather than solely practicing specific psychometrically-assessed spatial abilities in isolation, students would be taught how to *draw upon* their spatial abilities when thinking critically and solving problems. Researchers have tested ways of teaching spatial thinking in this way through teaching students how to solve spatially-related problems using geospatial technologies – GIS in particular. Unfortunately, many of those studies contain methodological flaws that render their results inadequate as evidence support the utility of using GIS as a spatial learning tool. As a result, there is a need for evaluations of the utility of GIS-based spatial learning. The current study was designed to contribute to the literature on spatial thinking by examining the potential effects of GIS-based spatial learning on both spatial abilities and SIC.

Taken together, the results from this dissertation provide preliminary evidence to support the utility of GIS-based spatial learning approaches for teaching both spatial abilities and SIC. Here I discuss the implications of my findings in terms of my three main questions.

Question 1: To what degree does participation in spatially-based learning (GSS) lead to improvement in spatial ability?

My results suggest that participation in GIS-based spatial learning can lead to certain improvements in participants' performance on psychometric tests of spatial ability. In our study, there was a significant effect of participation in GSS on participants' response time: over time, participants in the GSS condition showed a greater decrease in response time on EFT and MRT items compared to the comparison group. It is important to note that, while response times decreased in the GSS group, that group did not demonstrate significant improvement in EFT or MRT accuracy over time. As I argued in the previous section, it may be the case that participation in GSS led to an increase in confidence or comfort with responding to spatially-related questions.

Alternatively, other important aspects of spatial ability could be considered in addition to accuracy and response time – namely, participants' use of strategies to solve problems like the items in the EFT and MRT. For example, strategies frequently used on the MRT include mentally rotating one of the figures or counting the blocks in one figure and comparing the number of blocks to those of the other figure. The use of strategies on mental rotation tasks has been studied for many years (Boone & Hegarty, 2017; Kail, Carter, & Pellegrino, 1979; Kozhevnikov, Hegarty, & Mayer, 2002; Nazareth, Killick, Dick, & Pruden, 2018; Shepard & Metzler, 1971). Although much research has been dedicated to finding an optimal strategy for solving items on the MRT, recent research suggests that flexibility in applying strategies may be key: Nazareth and colleagues (2018) found that flexibility in strategy use was a significant predictor of MRT scores, even when controlling for gender. Based on their findings showing that males tended to be more flexible in their selection of strategies than females, Nazareth et al. argued that the gender disparity in MRT performance could potentially be explained by males' tendency to be more flexible in strategy application on spatial ability tasks like the MRT (see also Boone & Hegarty, 2017). As strategy use is an important factor in participants' success on tasks like the EFT and MRT, researchers may want to consider including measures that address participants' strategy use on these tasks in the future. Adding this type of measure in the future may help researchers understand whether participation in GIS-based spatial learning affects individuals' strategy choice and flexibility when solving spatial problems.

Finally, while these results concerning spatial ability and participation in the GSS are informative, they are based on performance on just two measures of spatial ability in a sample of seventy-six students. It is possible that participation in the GSS led to other improvements in spatial ability that were not measured by the EFT and MRT. However, based on the current findings from the EFT and MRT, I can only conclude that there is some preliminary evidence to support the utility of GIS-based spatial learning for promoting spatial ability, and more evidence is needed to support the efficacy of this type of approach for teaching spatial abilities.

Question 2: To what degree does participation in spatially-based learning (GSS) lead to improvement in spatial thinking in context?

My results suggest that participation in GIS-based spatial learning can lead to improvements in SIC. First, I found that participants in the GSS condition alone showed improvement in their use of spatial problem-solving strategy – specifically, the skill of knowing when, how, and why to use a spatial representation as a problem-solving tool. This finding suggests that participants are adopting the strategy of using spatial representations as they solve problems spontaneously and independently. The fact that they choose to do so when solving the hypothetical scenario problems also suggests that they were framing the problems as solvable by spatial means, and this may signal a shift in their ability to flexibly apply spatial thinking as they approach new problems. With that said, it is worth noting that, while the GSS group did demonstrate significant improvement in spatial representation use over time compared to the comparison group, they still scored relatively low on the rubric, on average, at Time 2. This may be due in part to terms of the coding rubric, participants' explanations of how and why they would use a spatial representation were fairly brief and could have been supported with more justification concerning *how* and *why* they chose to use that particular form of spatial representation. For example, a participant who simply indicated that she would "look at" a map could have instead provided more rationale for the map's use by explaining how the features of a map might be useful for helping her find a space for a new landfill. Specifically, she could look at the features of the map that would help her rule out areas where the landfill should not be placed (*e.g.,* near bodies of water). In addition, it is important to consider the fact that participants were presented with hypothetical questions and no instruction for how they should respond. While this type of questioning provided a benefit in that it allowed me to understand participants' spontaneous thinking about potentially spatially-related situations, it may have also led to some ambiguity regarding the focus of the question. In the future, it may be beneficial to ask participants to explain *why* or *how* they arrived at a certain choice or conclusion when deciding to use spatial data or spatial representations. For example, experimenters may want to use pointed follow-up questions to clarify participants' statements and probe their reasoning (e.g., "You said you would like to use a map. Can you tell me *how* using a map would help you solve this problem?").

Analysis of when participants elected to use spatial representations revealed some interesting patterns. At Time 2, 11 out of 35 GSS participants stated that they intended to use some sort of spatial representation when solving their hypothetical problem. Out of those 11 participants, 9 mentioned that they would use GIS specifically. Thus many of the GSS participants thought of GIS when asked to solve a novel problem. The analysis of spatial representation use across both groups revealed that participants only intended to use spatial representations in the *landfill* and *water treatment plant* scenarios (and not when solving the *gas, milk, political campaign,* or *recycling campaign* questions – refer to Appendix H for a full list of all six hypothetical scenario questions posed during the participant interviews). This may be the case because the *landfill* and *water treatment plant* scenarios were the only two scenarios that contained questions asking *where* one might place a new landfill or water treatment plant. Thus, participants may have been cued to the idea that those two problems were more spatial in nature. As previously discussed, the aim for GSS instruction – and for teaching SIC skills - is to teach students how to frame a variety of problems as spatial in nature, so in the future researchers may wish to study additional strategies for teaching students how to frame problems spatially.

The analysis of the second major spatial problem-solving skill – the use of spatial data – did not yield a significant finding. One explanation for this was the nature of the coding. Although inter-rater reliability was fairly high (Cohen's weighted $\kappa = .703$ (95% CI, .461 to .945, $p < .0005$), both coders found the coding of the use of spatial data to be more ambiguous and more variable by question type than the coding of spatial representation use. Future research may focus on finding ways of posing questions to participants that emphasize which information should be included in the response.

The other measures of SIC – the Spatial Habit of Mind Inventory (Kim & Bednarz, 2013a) and spatial word count, revealed null or mixed results. The SHOMI scores for the GSS group did increase over time in their overall score, but the interpretation of this growth is constrained by the fact that the comparison group actually decreased (slightly) over time, so there is no simple way to gauge the GSS group's progress in this context. The spatial word count

(LIWC) did not reveal a difference between groups' performance over time. This was unexpected because the findings of Jant et al. (who conducted a very similar study) showed that the GIS group increased in their spatial word use over time, while their control group did not. The fact that our GSS group did not show change in their use of spatial words may be due to differences in the length of response.

Given these findings, I conclude that there is some preliminary evidence that participation in GSS led to improvements in SIC – particularly with respect to spatial problem-solving - but more evidence is needed to determine *how* participation in this type of learning serves to promote SIC.

Question 3: To what degree are spatial ability and spatial thinking in context related?

Results from my analyses revealed an association between participants' performance on measures of SIC and measures of spatial ability, and this provides support for the argument that SIC skills and spatial abilities may be related. Regardless of timepoint (Time 1 or Time 2) or condition, higher scores on SHOMI were correlated with increased accuracy on both the EFT and MRT, and spatial representation use score was negatively correlated with response times on EFT and MRT. These findings are consistent with the argument that SIC skills are built on the application of basic spatial abilities. The relation between spatial ability and SIC merits further study. First, the nature of relations between the two levels of spatial thinking need to be investigated in terms of cause and effect: does training and learning in one level of spatial thinking promote change in the other? Many researchers have argued that the training of spatial abilities alone is not sufficient for promoting SIC skills (Bednarz & Bednarz, 2008; Bednarz & Kemp, 2011; National Research Council, 2006; Newcombe, 2006). However, it is possible that directly teaching some SIC skills (such as teaching high school students the meaning of *spatial* *habits of mind* and engaging them in the practices of noticing and learning about patterns in everyday life, creating spatial visualizations, etc.), may influence spatial abilities. Evidence from the current investigation does suggest that higher levels spatial habits of mind are associated with better spatial ability, but this finding needs to be replicated and investigated in with an experimental design. In the future, researchers who plan to study this relation should consider including measures of general cognitive ability (*e.g.,* executive function, general intelligence) to rule out the possibility that associations between performance on measures of spatial ability and SIC are primarily explained by cognitive abilities.

Future Directions

In the current study, we focused on coding participants' verbal responses to problem-solving questions and their performance on psychometric tests of spatial ability. For SIC measures in particular, much information was obtained from participants' verbal responses, it may be beneficial in the future to also code participants' use of gesture. While gesture and speech often convey similar information (Goldin-Meadow & Alibali, 2013), gesture can serve as a complement to speech in that it may communicate information that is not expressed in speech alone (Goldin-Meadow, 2005). Gesture is important to the communication of spatial information, as studies have shown that, on average, people tend to gesture twice as much when speaking about spatial topics than when speaking about non-spatial topics (Alibali, Heath, & Meyers, 2001; Lavergne & Kimura, 1987). As participation in GIS-based spatial learning is hypothesized to promote spatial thinking, it is possible that GIS students' spatial thinking would be expressed through their use of gesture. Specifically, I would hypothesize that, when presented with novel problem-solving scenarios that may or may not be solved in a spatial manner, students who frame a given problem as more spatial in nature will produce more gestures when explaining how they would solve that problem (see Alibali, 2005). This hypothesis would be best evaluated in a study much like ours in which GIS students and comparison group students solve novel scenario problems before and after the academic year. Gesture use could be coded and analyzed in conjunction with participants' verbal responses in order to better understand how participation in GIS-based spatial learning leads to changes in spatial thinking.

Future research may also benefit from studying the effects of GIS-based spatial learning on children and adolescents of varying ages. The current study's sample was comprised of juniors and seniors in high school, and other studies on GIS and spatial thinking have studied college-age students. There may be potential benefits of guided GIS use for spatial thinking may justify investigating the possibility of teaching younger adolescents or even middle schoolers how to use geospatial technologies (Bodzin, 2011). Collins and Halverson (2009) argue that, as various forms of technology become more prevalent for child and teenagers, educators should take advantage of students' increasing interest in (and access to) forms of technology, and I argue that this way of thinking may apply to geospatial technologies: educators may capitalize on students' interest in technology as a way to making spatial thinking more meaningful and accessible.

Some researchers have investigated the effects of geospatial technology use with children as young as twelve years of age (Bodzin, 2011; Perkins et al., 2010; Viehrig, 2015). Yet some of the studies on GIS use in younger students have results that are difficult to interpret due to small samples sizes, limited amounts of exposure to GIS (1 to 2 lessons, in some cases) or lack of a control group. Therefore, it may be worthwhile to conduct research on geospatial technologies and spatial thinking in younger students. Of course, researches will need to adjust GIS instruction to be developmentally appropriate and suit students' interests, but if researchers find ways to teach GIS use to younger students using instructional methods similar to those of the GSS, they could assess whether geospatial technologies could serve as a practical and useful tool for teaching spatial thinking skills at earlier ages.

The Potential Role of the GeoSpatial Semester in Promoting Spatial Ability and SIC

Collectively, the findings from this dissertation provide some evidence to suggest that GIS-based spatial learning can serve as an effective way to promote spatial abilities and teach spatial thinking in context, as participants who completed the GSS demonstrated some improvement in spatial ability and spatially-based problem-solving skill. What features of GSS instruction and learning may lead to success in promoting spatial ability and SIC?

Perhaps the most distinguishing feature of the GSS is that it is a STEM course designed to teach spatial thinking. This means that GSS students engage in real scientific practices, from data collection, analysis, and interpretation all while being taught to think spatially. GSS instructors teach students spatial abilities and SIC skills through the hands-on nature of the course: students engage in real-world problem-solving by learning to use spatial data and spatial representations as problem-solving tools. For example, students are taught to seek out sources of data and use the features of GIS to help them identify patterns and anomalies within their datasets. This act of creating their own visual representations provides students with a visuospatial and conceptual basis for understanding patterns and relationships in their data. Additionally, there are three other main factors that may drive the spatial learning in GSS.

GSS students solve real-world problems spatially. First, GSS instructors provide students with hands-on experience with spatial technology in *meaningful* and *relevant* problem-solving contexts. Students and teachers choose the topics of their investigations based on their interests and current events, and this enables students to stay motivated and excited about their work. As students learn about real-world issues for investigation in the GSS, they gain experience in identifying the spatial aspects of a problem and learn how to see novel problems as potentially solvable by spatial means. When students are able to understand the spatial elements of a problem, they are better able to construct a path to a solution by selecting sources of appropriate spatial data and recognize if and how the use of spatial representations (such as GIS) may be useful. In addition, when students practice understanding problems in terms of space, they may extend this practice into their everyday lives.

Students learn to use GIS <u>through</u> spatial problem-solving. In many college-level GIS courses, students first learn to master GIS skills (through textbook activities or laboratory activities), and subsequently use those skills in problem-solving in class projects and activities (Bearman et al., 2016). By contrast, students in the GSS begin their course by learning some basic GIS skills, but then begin to use the software as a spatial problem-solving tool. That is, they learn GIS skills in the context of their problem-solving processes and learn the mechanics of GIS by using the features as they are relevant to their problem-solving processes. This characteristic of GSS instruction is important because students may learn the spatial concepts associated with GIS functions better when they are able to understand as they apply to the context of their investigations of real-world phenomena (Bednarz, 2004).

Students learn to use geospatial technology independently. As the GSS course progresses, students learn to interact with GIS on a more sophisticated level and take increased ownership of their spatially-based learning. In particular, GSS students must prepare over the course of the year to be ready to complete an individual final project. At that point, students mimic the processes they have learned over the course of the year with their teacher and classmates. That is, each student selects a real-world problem to investigate and frames the problem so that it may be addressed by spatial means. They then seek out, collect, and analyze their own spatial data. Then, they use GIS to create detailed representations of their problem-solving process and final solution. Finally, students must complete an oral defense of their project to JMU faculty for questioning and feedback. The fact that this level of independence in SIC skills is expected of all students speaks to the mentality of instructors from the beginning of the course; the goal for GSS instruction is not to simply lead students through workshops or guide them through completing a disconnected array of GIS-related projects, but to engender a autonomy in spatial thinking. One of the key mechanisms of GSS may be the communication of the expectation that students will learn to work and problem-solve independently as spatial thinkers in the course, and that, for students, this degree of independence is attainable and worth pursuing.

Conclusion

When the National Research Council (2006) issued a call to researchers to focus on designing and testing ways to teach spatial thinking, they reported that spatial thinking was not being taught at a systematic level in the United States. Addressing this issue is difficult but is also of the utmost importance, particularly for education. The increasing popularity of geospatial technology use in educational settings (Baker et al., 2014; Bearman, Jones, André, Cachinho, & DeMers, 2016; Gordon, Elwood, & Mitchell, 2016) warrants the attention of researchers, because while there is great potential for teaching spatial skills using geospatial technology, when used ineffectively, may not teach spatial thinking skills (Baker & Bednarz, 2003; Baker et al., 2012; Bednarz, 2004). This dissertation sought to contribute to the literature by investigating the effects of a year-long implementation of a GIS-based spatial learning experience. This investigation has yielded preliminary evidence to suggest that participation in this type of learning can lead to some improvements in spatial ability and spatial thinking in context. As we continue to investigate how and why geospatial technology use impacts spatial thinking, we will find better and more effective ways of teaching spatial skills.

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Appendix A
Demographic information questionnaire for participants

1. **What grade will you enter in Fall 2016?**
   ☐ 9 ☐ 10 ☐ 11 ☐ 12

2. **What is your date of birth (month/day/year)?** _________/__________/___________

3. **How old are you?** ________

4. **Gender (e.g., male, female)**: _________________________

5. **Race** (check any that apply):

   ☐ Caucasian/White
   ☐ American Indian or Alaska Native
   ☐ Asian
   ☐ Native Hawaiian or Pacific Islander
   ☐ Black or African American
   ☐ Mixed Race/Other – Please Specify__________________________

6. **Ethnicity**
   ☐ Hispanic or Latino ☐ Not Hispanic or Latino

7. **Are you right handed or left handed?**
   ☐ Right handed ☐ Left handed ☐ Both (please describe: _______________)

8. **Are you a native speaker of English?** ☐ Yes ☐ No

   If no, how many years have you attended an English-speaking school? ______

9. **What do you think you'll be doing the September after you graduate from high school?** Check all that apply.

   ☐ In College/Community College/Technical School: What do you think will be your major/area of study? ______________________________

   ☐ Military: What kind of training will you be receiving? ____________________

   ☐ Working: Do you have a job lined up? YES NO

IF YES, doing what? ______________________________

IF NO, what kind of job do you think you'll be doing?______________________

10. How far do you think you will go in school? Check only the box next to the highest level of education you think you will get.

☐ Graduate from high school

☐ Post high school vocational or technical training

☐ Some college

☐ Graduate from a 2-year college or business college with an Associate's degree
If you checked this, what would you like to study? ____________________

☐ Graduate from a 4-year college or university
If you checked this, what would you like to study? ____________________

☐ Get a Master's degree
If you checked this, what would you like you to study? ____________________

☐ Get a law degree, a Ph.D., or a medical doctor's degree or similar
If you checked this, what would you like to study? ____________________

11. If you could have any job you wanted, what job would you like to have when you finish all your schooling? __________________________

12. Do you live with your biological mother?

☐ Yes ☐ No

13. Did your biological mother graduate high school or get her GED?

☐ Yes ☐ No ☐ I don't know

13a. <u>If yes</u>, what degrees did your biological mother earn? *Check all that apply.*

☐ High school diploma (or GED equivalency)

☐ Graduated from a 2-year college or technical school (or earned an Associate's degree)

☐ Graduated from a 4-year college or university (or earned a Bachelor's degree)

☐ Completed post-graduate studies (such as a master's degree, doctoral degree, law degree, etc.) after graduating from a 4-year college

☐ Other –Please describe: _________________

☐ I don't know

14. Are you aware of any companies in the local area that use Geospatial Information Systems (GIS)?

☐ No

☐ Yes; please name the companies you know:

____

15. Do any of your parents, relatives, neighbors, or family friends work in a company that uses Geospatial Information Systems (GIS)?

☐ No

☐ Yes; please describe: ____

16. Have you ever used Geospatial Information Systems (GIS) mapping software such as ArcGIS in any of your classes?

☐ No

☐ Yes; please describe: ____

Some students will be invited to participate in follow-up research sessions at Georgetown University where they will have their brain scanned while answering some questions. If you participate, you will be asked to lie on a long narrow bed inside a MRI scanner while the machine takes pictures and gathers information. During scanning, you will be exposed to a magnetic field and radio waves, but will not feel them.

Students who participate will be compensated for traveling to Georgetown University and will get to see a picture of their brain!

17. Would you consider having your brain scanned as part of this research study?

____ Yes ____ Maybe ____No

18. Are you claustrophobic (afraid when in small confined spaces)?

_____ Yes _____No _____I don't know

19. Do you have any metal in your body that you can't remove? (examples: metal braces on your teeth, piercings you can't remove, metal joints, pacemaker, hearing aid)

_____ Yes _____No _____I don't know

Appendix B
Spatial Habits of Mind Inventory
Kim & Bednarz (2013a)

Habits of Mind Inventory

Please circle one response for each item that best describes your thoughts, beliefs, or actions. There are no right or wrong answers.

	Strongly Disagree	*Disagree*	*Neutral*	*Agree*	*Strongly Agree*
1. I tend to see patterns among things, for example, an arrangement of tables in a restaurant or cars in a parking lot.	**SD**	**D**	**N**	**A**	**SA**
2. I rarely use spatial vocabulary such as "location," "direction," "diffusion," and "network."	**SD**	**D**	**N**	**A**	**SA**
3. When I am thinking about a complex idea, I use diagrams, maps, and/or graphics to help me understand.	**SD**	**D**	**N**	**A**	**SA**
4. When trying to solve some types of problems, I tend to consider location and other spatial factors.	**SD**	**D**	**N**	**A**	**SA**
5. I use maps and atlases (including digital versions) frequently.	**SD**	**D**	**N**	**A**	**SA**
6. I tend to see and/or search for regularity in everyday life when viewing objects or phenomena.	**SD**	**D**	**N**	**A**	**SA**
7. I use spatial terms such as scale, distribution, pattern, and arrangement.	**SD**	**D**	**N**	**A**	**SA**
8. It is difficult for me to construct diagrams or maps to communicate or analyze a problem.	**SD**	**D**	**N**	**A**	**SA**
9. I do not pay attention to reading and interpreting spatial patterns such as locations of cars in a parking lot.	**SD**	**D**	**N**	**A**	**SA**
10. Using spatial terms enables me to describe certain things more efficiently and effectively.	**SD**	**D**	**N**	**A**	**SA**
11. When a problem is given in written or verbal form, I try to transform it into visual or graphic representation.	**SD**	**D**	**N**	**A**	**SA**
12. When I assemble something such as furniture, a bicycle, or a computer, written instructions are more helpful to me than pictorial instructions.	**SD**	**D**	**N**	**A**	**SA**

	Strongly Disagree	*Disagree*	*Neutral*	*Agree*	*Strongly Agree*
13. I like to use spatial tools such as maps, Google Earth, or GPS.	**SD**	**D**	**N**	**A**	**SA**
14. I have difficulty in explaining spatial concepts such as scale and map projection to my friends.	**SD**	**D**	**N**	**A**	**SA**
15. I do not like using maps and atlases (including digital versions).	**SD**	**D**	**N**	**A**	**SA**
16. When I use maps to find a route, I tend to notice overall patterns in the road network.	**SD**	**D**	**N**	**A**	**SA**
17. I have difficulty in describing patterns using spatial terms, such as patterns in bus routes or in the weather.	**SD**	**D**	**N**	**A**	**SA**
18. I find that graphs, charts, or maps help me learn new concepts.	**SD**	**D**	**N**	**A**	**SA**
19. When reading a newspaper or watching news on television, I often consider spatial concepts such as location of the places featured in the news story.	**SD**	**D**	**N**	**A**	**SA**
20. I enjoy looking at maps and exploring with mapping software such as Google Earth and GIS.	**SD**	**D**	**N**	**A**	**SA**
21. I am curious about spatial patterns in information or data, that is, where things are and why they are where they are.	**SD**	**D**	**N**	**A**	**SA**
22. It is helpful for me to visualize physical phenomena such as hurricanes or weather fronts to understand them.	**SD**	**D**	**N**	**A**	**SA**
23. Spatial concepts, such as location and scale, do not help me solve problems.	**SD**	**D**	**N**	**A**	**SA**
24. Activities that use maps are difficult and discourage me.	**SD**	**D**	**N**	**A**	**SA**
25. When I use maps showing things such as population density, election results, or highways, I try to recognize patterns.	**SD**	**D**	**N**	**A**	**SA**
26. I like to support my arguments/presentations using maps and diagrams.	**SD**	**D**	**N**	**A**	**SA**
27. I tend to use spatial terms such as "location," "pattern," or "diffusion" to describe phenomena.	**SD**	**D**	**N**	**A**	**SA**

	Strongly Disagree	*Disagree*	*Neutral*	*Agree*	*Strongly Agree*
28. I like to study data or information with the help of graphics such as charts or diagrams.	**SD**	**D**	**N**	**A**	**SA**

Appendix C
Spatial Habit of Mind Subcomponents (SHOMI)

Spatial habit of mind subcomponent	Description	Sample SHOMI item
1. Pattern recognition	Engaging in pattern recognition by attempting to detect spatial patterns in everyday situations, describing spatial patterns, and forming predictions or explanations based on trends in spatial information	When I use maps to find a route, I tend to notice overall patterns in the road network.
2. Visualization	Creating one's own external visual spatial representations in order to enhance the understanding of spatial information or to convey spatial information to an audience	When a problem is given in written or verbal form, I try to transform it into visual or graphic representation.
3. Spatial description	Using spatial language to communicate spatial information to others in an everyday context (e.g., when explaining the concept of gerrymandering to a friend by using vocabulary related to the concept of population density ("compact," "disperse").	I tend to use spatial terms such as location, pattern, or diffusion to describe phenomena.
4. Spatial concept use	The habit of considering concepts related to external spatial representations (e.g., map-like: location, scale, perspective, projection) to enhance one's understanding of a real-world situation, as in when an artist paints a representation of an imaginary landscape by first considering aspects of scale, viewpoint, and direction in the intended spatial layout of her painting.	When trying to solve some types of problems, I tend to consider location and other spatial factors.
5. Spatial tool use	The habit of using spatial tools (e.g., GPS, maps, Geographic Information Systems) to assist in the navigation of physical environments and enhance the understanding of spatial data. A driver in a new city might use a paper map to help him find his way to a new landmark, or a pedestrian looking for the fastest walking route to work may use Google Maps to select an optimal path.	I like to use spatial tools such as maps, Google Earth, or GPS.

Appendix D

Condition and Sex Differences at Time 1 (Full Report of Preliminary Analyses)

For both of my EFT and MRT analyses, I analyzed participants' accuracy (or the proportion of correct responses out of the total number of trials) as well as their response time (in milliseconds). For the accuracy measures for EFT and MRT, scores represent the proportion of correct responses out of the total number of items, so on a scale from 0 – 1.0, thus a higher score represents better accuracy. Response times for EFT and MRT show the amount of time that elapsed from the start of the EFT or MRT trial until the participant responded.

MRT accuracy at Time 1. Results of a two (condition: GSS, Comparison) by two (gender: Male, Female) factorial ANOVA on Time 1 MRT accuracy scores revealed a marginally-significant main effect of condition such that participants in the comparison group scored higher on proportion of MRT trials correct, ($M = .792$, $SD = .139$) than participants in the GSS group ($M = .751$, $SD = .125$), $F(1, 104) = 3.95$, $p = .05$, $\eta^2_p = .04$. There was a significant main effect of gender; males ($M = .811$, $SD = .122$) scored higher than females ($M = .729$, $SD = .135$), $F(1, 104) = 11.62$, $p = .001$, $\eta^2_p = .10$. There was no significant interaction between gender and condition, $p > .05$.

MRT response time at Time 1. Results of a two (condition: GSS vs. comparison) by two (gender: male vs. female) factorial ANOVA on Time 1 MRT response times revealed a main effect of condition. On average, the comparison-group participants responded more rapidly ($M =$ 3820 ms, $SD = 608$ ms) than GSS-condition participants did ($M = 4149$ ms, $SD = 499$ ms), $F(1, 104) = 8.56$, $p = .004$, $\eta^2_p = .08$. There was no significant main effect of gender and no significant interaction between gender and condition, ps > .05.

EFT accuracy at Time 1. Results of a two (condition: GSS, comparison) by two (gender: male, female) factorial ANOVA on Time 1 EFT accuracy scores revealed a main effect of condition. Comparison-group participants scored higher (*M* = .689, *SD* = .170) than GSS-participants did (*M* = .608, *SD* = .178), on EFT accuracy, $F(1, 107) = 8.36$, $p = .005$, $\eta^2_p = .07$. Additionally, there was a main effect of gender such that males responded more accurately (*M* = .696, *SD* = .154) than females (*M* = .597, *SD* = .189), $F(1, 107) = 11.33$, $p = .001$, $\eta^2_p = .09$.

EFT response time at Time 1. Results of a two (condition: GSS, comparison) by two (gender: male, female) factorial ANOVA on Time 1 EFT response time revealed no significant main effects or interaction.

Appendix E
Correlations Between SIC and Spatial Ability Measures

Pearson Correlations

		SHOM_all	LIWC_all	EFT_acc_all	EFT_RT_all	MRT_acc_all	MRT_RT_all
SHOM_all	Pearson's r	—					
	p-value	—					
LIWC_all	Pearson's r	0.135	—				
	p-value	0.098	—				
EFT_acc_all	Pearson's r	0.204*	0.133	—			
	p-value	0.012	0.102	—			
EFT_RT_all	Pearson's r	−0.061	0.015	−0.133	—		
	p-value	0.457	0.855	0.102	—		
MRT_acc_all	Pearson's r	0.167*	0.038	0.291***	−0.216**	—	
	p-value	0.040	0.642	< .001	0.007	—	
MRT_RT_all	Pearson's r	−0.069	−0.052	−0.228**	0.461***	−0.418***	—
	p-value	0.401	0.523	0.005	< .001	< .001	—

* p < .05, ** p < .01, *** p < .001

Appendix F
Correlations between Spatial Data Use, Spatial Representation Use, and Other Variables

Spearman Correlations

		SHOM_all	LIWC_all	EFT_acc_all	EFT_RT_all	MRT_acc_all	MRT_RT_all	Sp_data_all	Sp_rep_all
SHOM_all	Spearman's rho	—							
	p-value	—							
LIWC_all	Spearman's rho	0.107	—						
	p-value	0.190	—						
EFT_acc_all	Spearman's rho	0.175*	0.126	—					
	p-value	0.031	0.121	—					
EFT_RT_all	Spearman's rho	−0.100	0.006	−0.129	—				
	p-value	0.221	0.938	0.114	—				
MRT_acc_all	Spearman's rho	0.096	0.073	0.331***	−0.208*	—			
	p-value	0.240	0.373	< .001	0.010	—			
MRT_RT_all	Spearman's rho	−0.075	−0.115	−0.218**	0.430***	−0.475***	—		
	p-value	0.356	0.157	0.007	< .001	< .001	—		
Sp_data_all	Spearman's rho	0.009	0.201*	0.131	−0.118	0.252**	−0.027	—	
	p-value	0.912	0.014	0.110	0.150	0.002	0.742	—	
Sp_rep_all	Spearman's rho	0.186*	0.068	0.007	−0.177*	−0.055	−0.203*	−0.043	—
	p-value	0.023	0.410	0.928	0.030	0.501	0.013	0.600	—

* p < .05, ** p < .01, *** p < .001

Appendix G
List of spatial words ("dictionary") used in LIWC analysis

All of the words in the column on the left were included in the LIWC analysis. The column in the middle indicates whether the word was included in Pennebaker et al.'s dictionary. The column on the right indicates whether the word was included in Cannon et al.'s dictionary. Words in bold in the left column appeared in both dictionaries, and an asterisk (*) at the end of the word signals to LIWC that the word may be counted if it appears with that beginning. For example, the word "border" is marked with an asterisk, signaling to LIWC that variations on that word (such as "bordered" or "borders") may be counted as spatial words also.

Final spatial word list (dictionary) used with LIWC	Appears in Pennebaker et al. dictionary	Appears in Cannon et al. dictionary
about		x
above	x	x
across	x	x
air	x	
after		x
against		x
ahead		x
all		x
along		x
among*	x	x
amount		x
amounts		x
angle		x
angles		x
anterior	x	
anywhere	x	x
apart	x	x
arc		x
arcs		x
area*	x	x
around	x	x
aside		x
at	x	x
atlas		
attribute		
atop	x	x
avenue*	x	
away	x	x
axes		x

axis		x
back	x	x
backward*	x	x
barrier		
basemap		
before		x
behind	x	x
below	x	x
bend	x	x
bending	x	
bends	x	x
bendy		x
beneath	x	x
bent	x	x
beside	x	x
between		x
beyond	x	x
big	x	x
bigger	x	x
biggest	x	x
bit		x
bits		x
border*	x	x
both	x	
bottom	x	x
bottomless	x	
breadth	x	
brink	x	
broad	x	
broader	x	
broadest	x	
buffer		
bumfuck	x	
bump		x
bumped		x
bumps		x
bumpy		x
by		x
capacit*	x	x
ceiling*	x	
center*	x	
central*	x	

centre*	x	
centimeter		x
centimeters		x
circle		x
circles		x
circular		x
city	x	
close	x	x
closed	x	
closely	x	
closer	x	x
closest	x	x
column*	x	x
cone		x
cones		x
conical		x
connection*	x	
contain*	x	
coordinates		
corner	x	x
corners	x	x
counties	x	
countr*	x	
county	x	
coverage	x	
cube		x
cubes		x
curve		x
curved		x
curves		x
curvy		x
cylinder		x
cylinders		x
cylindric		x
cylindrical		x
data		
decrease		x
decreased		x
decreases		x
decreasing		x
deep	x	x
deeper	x	x

deepest	x	x
deeply	x	
dense	x	
densit*	x	
depth*	x	x
design		x
designs		x
diagonal*	x	x
diamond		x
diamonds		x
dimension*	x	
direct	x	
direction*	x	x
directly	x	
dissolve		
distal	x	
distan*	x	x
district	x	
door*	x	
down	x	x
downer		x
downhill	x	
downstairs	x	
downtown	x	
downward*	x	x
earth	x	
east*	x	x
edge*	x	x
eight		x
eights		x
ellipse		x
ellipses		x
elliptical		x
elsewhere	x	
emptier		x
emptiest		x
emptiness	x	
empty	x	x
enclos*	x	
encompass*	x	
enorm*	x	x
enough		x

entrance*	x	
environment*	x	
equal		x
everywhere*	x	x
exit*	x	
expand*	x	
exterior*	x	
far	x	x
farer		x
farest		x
farther	x	
farthest	x	
fat		x
fatter		x
fattest		x
feet		x
fifth		x
fifths		x
fill*	x	
first		x
fit	x	
flat	x	x
flatter		x
flattest		x
flip		x
flipped		x
flipping		x
flips		x
floor*	x	
foot		x
forward	x	x
forwarded	x	
forwarding	x	
forwards	x	
foundation*	x	
fraction		x
fractions		x
fragment		x
fragments		x
from		x
front	x	x
full	x	x

fuller	x	x
fullest	x	x
fullness	x	
fully	x	
further	x	x
furthering	x	
gap	x	
gate*	x	
giant	x	
gigantic	x	x
ginormous	x	
global*	x	
globe		x
globes		x
ground*	x	
half		x
hall	x	
halves		x
head		x
headed		x
heading		x
heads		x
height*	x	x
here		x
hexagon		x
hexagons		x
high	x	x
higher	x	x
highest	x	x
hole*	x	
horizontal*	x	x
huge	x	x
hugely	x	
huger	x	
hugest	x	
in	x	x
inch*	x	x
increase		x
increased		x
increases		x
increasing		x
indirect*	x	

inferior	x	
inner*	x	
inside	x	x
insides	x	
interior*	x	
internal	x	
internally	x	
internation*	x	
intersect*	x	
intertwine	x	
intertwined	x	
into	x	x
itsy-bitsy		x
itty-bitty		x
join		x
joined		x
kilometer*	x	x
km*	x	
land	x	
large	x	x
largely	x	
larger	x	x
largest	x	x
last		x
lateral	x	
latitude		
layer		
ledge*	x	
left	x	x
leftward		x
lengthwise		x
length	x	x
lengths		x
less		x
level	x	
levels	x	
lil	x	
lil'	x	
line		x
linear	x	
lines		x
link*	x	

little	x	x
littler	x	x
littlest	x	x
local	x	
locale*	x	
localis*	x	
localit*	x	
localiz*	x	
locally	x	
locals	x	
locat*	x	x
long	x	x
longer	x	x
longest	x	x
longitud*	x	
lot		x
low	x	x
lower	x	x
lowered	x	
lowering	x	
lowers	x	
lowest	x	x
lowli*	x	
lowly	x	
lump		x
lumps		x
lumpy		x
map	x	
mapped	x	
mapping	x	
maps	x	
mass	x	
massive	x	
measure		x
measurements		x
measures		x
medial*	x	
meter*	x	x
metre*	x	
mid	x	
middle	x	x
mile*	x	x

mixed	x	
model		
more		x
much		x
narrow	x	
narrowed	x	
narrower		x
narrowest	x	x
narrowing	x	
narrowly	x	
narrowness	x	
narrows	x	
nation	x	
national	x	
nationality	x	
nationally	x	
nationals	x	
nations	x	
near	x	x
nearby		x
neared	x	
nearer	x	
nearest	x	
nearing	x	
nears	x	
neighbor*	x	
neighbour*	x	
next		x
ninth		x
ninths		x
none		x
north*	x	x
nowhere	x	x
octagon		x
octagons		x
off	x	x
on	x	x
onto	x	x
open	x	
opened	x	
opening*	x	
opens	x	

opposite		x
order		x
orders		x
orientation		x
orientations		x
out	x	x
outer*	x	
outside	x	x
outsides	x	
outward*	x	
oval		x
ovals		x
over	x	x
overflow*	x	
overlap*	x	
parallel		x
parallelogram		x
parallelograms		x
part		x
parts		x
past		x
path		x
paths		x
pattern		x
patterns		x
pentagon		x
pentagons		x
perpedicular		x
perpendicular		x
piece		x
pieces		x
place	x	x
placed	x	
placement*	x	
places	x	
placing*	x	
plane		x
planes		x
platform*	x	
point	x	x
pointed		x
points		x

pointy		x
polygon		x
portion		x
portions		x
position*	x	x
posterior	x	
provinc*	x	
proxima	x	
proximity	x	
pyramid		x
pyramids		x
quadrilateral		
quadrilaterals		x
quarter		x
quarters		x
rectangle		x
rectangles		x
rectangular		x
region*	x	
remote*	x	
repeat		x
repeated		x
repeating		x
repeats		x
repetition		x
reverse		x
rhombus		x
rhombuses		x
right	x	x
rightward		x
rise*	x	
road*	x	
room	x	x
roomate*	x	
roomed	x	
roomie*	x	
rooming	x	
rooms	x	x
rotate		x
rotated		x
rotates		x
rotating		x

rotation		x
rotations		x
round		x
rounded		x
rounder		x
roundest		x
route*	x	x
row		x
rows		x
same		x
section	x	x
sections		x
sector*	x	x
segment*	x	x
semicircle		x
semicircles		x
separat*	x	x
sequence		x
sequences		x
seventh		x
sevenths		x
shallow		x
shallower		x
shallowest		x
shape*	x	x
shaping*	x	
short	x	x
shorter	x	x
shortest	x	x
shortly	x	
shut	x	
side	x	x
sided		x
sides	x	x
sideways		x
siding	x	
sit	x	
site	x	
sites	x	
sits	x	
sitting	x	
sixth		x

sixths		x
size		x
sizes		x
skinnier		x
skinniest		x
skinny		x
sky*	x	
small	x	x
smaller	x	x
smallest	x	x
some		x
somewhere	x	x
south*	x	x
space	x	x
spaced	x	
spaces	x	
spaci*	x	
span	x	
spann*	x	
spatial		
sphere		x
spheres		x
spheric		x
spherical		x
split*	x	
sprawl*	x	
square		x
squares		x
stair*	x	
stay	x	
stayed	x	
staying	x	
stays	x	
straight	x	x
straighter	x	x
straightest	x	x
street*	x	
stretch*	x	
stuck	x	
superior	x	
surfac*	x	x
surround*	x	

symmetric		x
symmetrical		x
symmetry		x
tall	x	x
taller	x	x
tallest	x	x
teeny		x
tenth		x
tenths		x
territor*	x	
there		x
thick*	x	x
thin	x	x
thinly	x	
thinned	x	
thinner	x	x
thinnest	x	x
third		x
thirds		x
through		x
throughout		x
tinier		x
tiniest	x	x
tiny	x	x
to		x
together	x	x
top	x	x
toward*	x	x
town	x	
triangle		x
triangles		x
triangular		x
turn		x
turned		x
turning		x
turns		x
under	x	x
underneath	x	x
undersid*	x	
universe*	x	
up	x	x
upon	x	

upper	x	x
uppermost	x	
upright	x	x
upstairs	x	
upto		x
upward		x
vast	x	
vastly	x	
vastness	x	
verg*	x	
vertical*	x	x
via	x	
volume		x
volumes		x
wall	x	
walls	x	
wave		x
waves		x
wavey		x
way	x	
west*	x	x
where	x	x
where'd	x	
where's	x	
wheres	x	
wherever	x	x
whole		x
wholes		x
wide	x	x
widely	x	
wider	x	x
widest	x	x
width*	x	x
with		x
within	x	x
world	x	

Appendix H
List of hypothetical scenario questions

Hypothetical Problem-Solving Scenario Questions
Milk Prices "Why do you think milk prices differ from brand to brand? How would you predict what the price would be for each brand?"
Recycling Campaign "If you were running a campaign to increase recycling by your community, how would you go about running your campaign?"
Landfill "If your city needed to add an additional landfill and you were in charge of the process, how would you go about determining where it should be located?"
Gas Prices "Why do you think gas prices differ from station to station? How would you predict what the price would be for each station?"
Political Campaign "If you were running a campaign for a local political office, how would you go about running your campaign?"
Water Treatment Plant "If your city needed to add an additional water treatment plant and you were in charge of the process, how would you go about determining where it should be located?"