GEOSPATIAL TECHNOLOGY TO ENHANCE SPATIAL THINKING AND FACILITATE PROCESSES OF REASONING

A Dissertation

by

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ABSTRACT

Research on spatial thinking in geography education supports the belief that spatial thinking is crucial to academic and career success in geography and other spatially-dependent sciences. It also supports the belief that spatial thinking is malleable, it can be improved upon through education and training. Tools purported to facilitate the training of spatial thinking include geospatial technologies (GST) such as Virtual Globes and Geographic Information Systems (GIS). The purpose of this study was to explore the influence of GST as an instructional tool on the development of spatial skills and the acquisition of a spatially-dependent geography concept, central place theory, within an authentic classroom context. A quasi-experimental design was used to compare three groups: an intervention group using GST, a comparison group using traditional paper-and-pencil maps, and a control group. Groups were tested on spatial skills, spatial attitudes, and content knowledge. Results indicate that practice with GST had no effect on spatial skills. Instruction using GST, however, had a significant positive effect on gains in content knowledge as compared to the paper-and-pencil group. Results also indicate that individuals with a high starting level of spatial skill have greater gains in spatial relations content knowledge than their low or average spatial skill counterparts, especially within the GST intervention group. These findings support the inclusion of GST in geography education. Geospatial technologies promote the acquisition of spatially-dependent content for some groups of students. Instruction utilizing GST may, with repeated exposure, facilitate the development of spatial thinking.

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CHAPTER I

INTRODUCTION

SPATIAL THINKING AND GEOGRAPHY

The ability to reason spatially is a defining element, perhaps the most important, to scientific, mathematical, and geographic competency**.** Strong spatial skills are positively correlated with success in geography and other sciences (Hsi, Linn, and Bell 1997; Kali and Orion 1996; Pallrand and Seeber 1984). Spatial skills are malleable and have been shown to improve with training (Lee and Bednarz 2009; Shin 2007; Terlecki 2004; Wright et al. 2008). Spatial thinking is a broad term that incorporates spatial cognition and spatial skills. It focuses on problem solving using spatial concepts, spatial representations, and spatial analysis. Spatial thinking requires the combination of three elements: concepts of space, tools of representation, and processes of reasoning (Committee on Support for Thinking Spatially 2006). It is concepts of space (e.g., distance, pattern, spatial association) that make spatial thinking distinct from other forms of thinking such as verbal or mathematical.

The report from the Committee on Support for Thinking Spatially (2006) identifies spatial thinking as a critical cognitive skill for everyday life, work, problem solving, and decision making. It advocates training in spatial thinking at all levels of K-12 education in order to foster spatial literacy and enhance understandings of spatial concepts in geography and science. Knowing spatial concepts and understanding when and how to utilize spatial concepts to answer questions and solve problems is an essential part of competence in life.

Geography includes many concepts and skills that require the ability to reason spatially such as creating or interpreting various types of maps or models, visualizing how geological structures transform over time, or utilizing theory to predict dynamic spatial patterns such as the size and shape of market centers. In geography spatial thinking allows unseen abstract processes to be represented mentally and supports inquiry about complex spatial phenomena (Committee on Support for Thinking Spatially 2006). Even though spatial thinking is important to geographic and scientific literacy, few attempts have been made to study the effect on student learning as a result of instruction of and attention to underlying cognitive spatial skills (Baker and Bednarz 2003; Mathewson 1999). Spatial skills are often assumed to be present, and therefore educators have developed few resources and lack pedagogy for the instruction of spatial thinking in the classroom.

Geospatial Technologies as a Tool to Facilitate Spatial Thinking

Geospatial technologies (GST) allow visualization, mapping, wayfinding, and analysis of features both concrete and conceptual on the Earth's surface and subsurface. GST include Geographic Information Systems (GIS), Remote Sensing (RS), Global Positioning System (GPS), and virtual globes such as Google Earth® and NASA's World Wind®. These technologies allow for the visualization and modeling of spatial patterns of phenomena from simple to complex that may otherwise go unnoticed due to issues of scale, complexity, accessibility, limited technology, or limited imagination. *Rediscovering Geography* (National Research Council 1997) stated that geographers would be responsible for educating future generations of GIS[1] users and that part of that responsibility would require facilitating students' understanding of geographic processes and spatial patterns, understanding spatial analysis, and utilizing spatial visualization techniques. Since 1997, the use of geospatial technologies has expanded from specialized use in a restricted capacity by a relatively small number of experts to very broad use by much of the general public. One way to interpret this is, if GIS is used now by the general public, then geography education should prepare all students as future GIS users with a need to understand geographic processes, spatial patterns, and spatial visualization techniques.

Bednarz (2004, 192) specifically states, "For geographic educators the most important and powerful argument for incorporating GIS into the curriculum is its purported ability to enhance spatial thinking skills." Bednarz also outlines three additional justifications for incorporating GIS into K-12 education; 1) GIS and GIScience support the teaching and learning of geography and environmental education, 2) GIS is an essential tool in the modern day workplace, and 3) GIS is an ideal tool for the study of environment and community. The Committee on Support for Thinking Spatially (2006) elaborated these justifications for GIS in K-12 classrooms by stating that GIS has the potential not only to enhance spatial skills but also to support the

[1] GIS is an example of one type of geospatial technology (GST). When using the term GIS, application to the broader context of geospatial technologies is implied.

scientific research process (e.g. inquiry), provide workforce opportunities in the information technology sector, and accommodate a diverse range of learners (age, learning style, and ability). Even though it is generally thought that GIS can enhance spatial thinking or that it is an ideal instructional tool, there is little empirical evidence to support this claim. This study aims to explore this question.

Research on Spatial Thinking

Spatial thinking is an important predictor of success in many academic disciplines such as chemistry (Wu and Shaw 2004), physics (Pallrand and Seeber 1984), geosciences (Kali and Orion 1996), and engineering (Hsi, Linn, and Bell 1997). It is also crucial beyond the classroom. Validating the spatial-vocational implications for spatial skills, Shea, Lubinski, and Benbow (2001) tracked over 563 intellectually gifted students from age 13 for 20 years to explore the relationship between their mathematical, verbal, and spatial abilities and their choice of college major and career. The study identified a "huge range" in spatial skills among this sample of highly intellectually gifted students. The majority of individuals who had strong spatial thinking skills, as measured by the space relations and mechanical reasoning subtests of the Differential Aptitude Test (DAT), majored in science and maintained careers in science after college. Another study supporting the importance of spatial skills in the workplace is the study by Keehner et al. (2006) which explored the spatial skills of surgeons first learning to use an angled laparoscope. The researchers found large variability in beginning level surgical skills that correlated positively with individual's spatial skills. Even though the variance in surgical skill diminished with practice, the correlation between performance and spatial skills remained substantial. Therefore, spatial thinking is important for success in spatial skill oriented careers (Committee on Support for Thinking Spatially 2006).

Spatial thinking is malleable. In a dissertation study by Terlecki (2004) training effects on mental rotation ability was retained over a period of four months with evidence of transfer to other visualization tasks. Similar to findings from other studies about the improvement of spatial thinking, individuals who initially scored poorly on a spatial-experience survey improved at a faster rate in training than those with high spatial experience. Terlecki also found large gender differences in spatial experiences, strategy choice for spatial problem solving, and in training effects. In general, males were much more likely to be ranked as "high spatial experience" and initially showed better performance on the mental rotation task. Although females and males made similar improvements in spatial skills with training, the performance gap remained. Studies such as Terlecki's do not provide evidence of transfer of acquired spatial skills to a domain-specific area such as geography. Even though there is a well-documented connection between spatial skills and academic performance, there is little evidence to indicate a correlation between gains in spatial thinking and success in learning spatial concepts or acquiring skill for novel spatial tasks. A second study by Wright et al. (2008) explores transfer from general spatial cognition to spatial skills. Similar to Terlecki, Wright et al. found robust training effects, but they also found there was better performance on a novel spatial task among individuals who had practiced a mental rotation task (spatial) as compared to those who practiced a verbal analogy task (non-spatial).

Improvement of spatial thinking through training is possible and feasible as demonstrated by the studies described above. The training tasks used in each of the studies reviewed previously were simple and easy to implement. Nevertheless, the cognitive science research literature does not establish a connection between the spatial skills assessed and the real-world student learning of spatial concepts. Research in this area lacks the ecological validity of a classroom setting to explore the effects of intentional and explicit spatial thinking training on the learning of spatial concepts.

In geography a few studies have linked the use of geospatial tools, specifically GIS, to spatial thinking and spatial concepts in a class setting. Working with undergraduate students, Lee and Bednarz (2009) found that the number of geo-technology courses (e.g., GIS or Computer Cartography) a student had completed positively affected his/her score on a spatial skills test. In addition, a student sub-group who completed a GIS course without any prior GST courses showed significant gains in spatial skills between pretests and posttests. This suggests that use of GIS facilitated gains in students' spatial thinking.

Working with elementary students, Shin (2007, 246) found that using GIS to teach geography enhanced geographic understanding and facilitated students' cognitive processes for understanding place. "The students' learning of place seemed to begin with a simple recognition of places and then they developed their sense of place by defining relationships among places." Shin's study did not specifically examine changes in students' spatial skills as measured by standard psychometric tests, but rather, using qualitative means, Shin established a positive relationship among the use of geospatial technology, student learning, and changes in students' cognitive strategies. From these applied classroom studies, it appears that practice in spatial thinking supports the acquisition of concept knowledge and the use of geospatial technologies supports the practice of spatial thinking.

GST can be used to foster content-specific educational goals and to bridge theory and practice (Pauwels 2006). Tools for geovisualization, such as GST, can be used to think about space at a high level of critical thought and reasoning. And, in some cases it can be used to "think with space [which] involves thinking with or through the medium of space in the abstract" (Committee on Support for Thinking Spatially 2006, 30). This context of thinking "with space" involves *spatializing* phenomena both physically bound and non-spatial. It is exemplified in cases such as using geovisualization to model climate change and in the production of conceptual maps to spatialize beliefs, perceptions, or the diffusion of ideas. Map use can facilitate the development of spatial cognition (Liben, Kastens, and Stevenson 2002; Lobben 2004; Uttal 2000). Specifically digital maps such as GIS and Google Earth© can be utilized in the classroom as appropriate geovisualization tools to facilitate spatial thinking and support content learning (Committee on Support for Thinking Spatially 2006; Kerski 2008).

PURPOSE OF THE STUDY

The objective for this study was to explore the effectiveness of GST as a tool for enhancing spatial thinking skills and for teaching a spatial concept in geography. In addition to assessing the effectiveness of GST as an instructional tool, this study explores the relationship among students' spatial thinking skills, attitudes towards spatial and navigational abilities, and changes in geography content knowledge.

Few projects have attempted to bridge understandings of the development of spatial thinking from the cognitive sciences to applied classroom research in the area of technological pedagogical content knowledge (TPCK) (Mishra and Koehler 2006). By building on theoretical foundations of how and under what circumstances spatial thinking can be nurtured and facilitated, this project aims to further understand the effect of explicit instruction in spatial thinking.

DESIGN OF THE STUDY

High school geography students were recruited for a quasi-experimental intervention design conducted in a classroom setting. Four classes were divided using a stratified random sample design dividing the classes first by sex then randomly into intervention and comparison groups. The intervention groups completed an instructional activity about central-place theory using Google Earth® with GIS. The comparison groups studied the same content using paper-and-pencil maps and tables. A fifth class served as a control group. This group did not receive instruction about central place theory or spatial thinking. Pretests and posttests were administered measuring spatial skills and content. A presurvey measuring students' self-reported sense of direction was also administered. Instructional content and delivery were consistent between the intervention and comparison groups with only the visuo-spatial tool for instruction and practice differing (Figure 1).

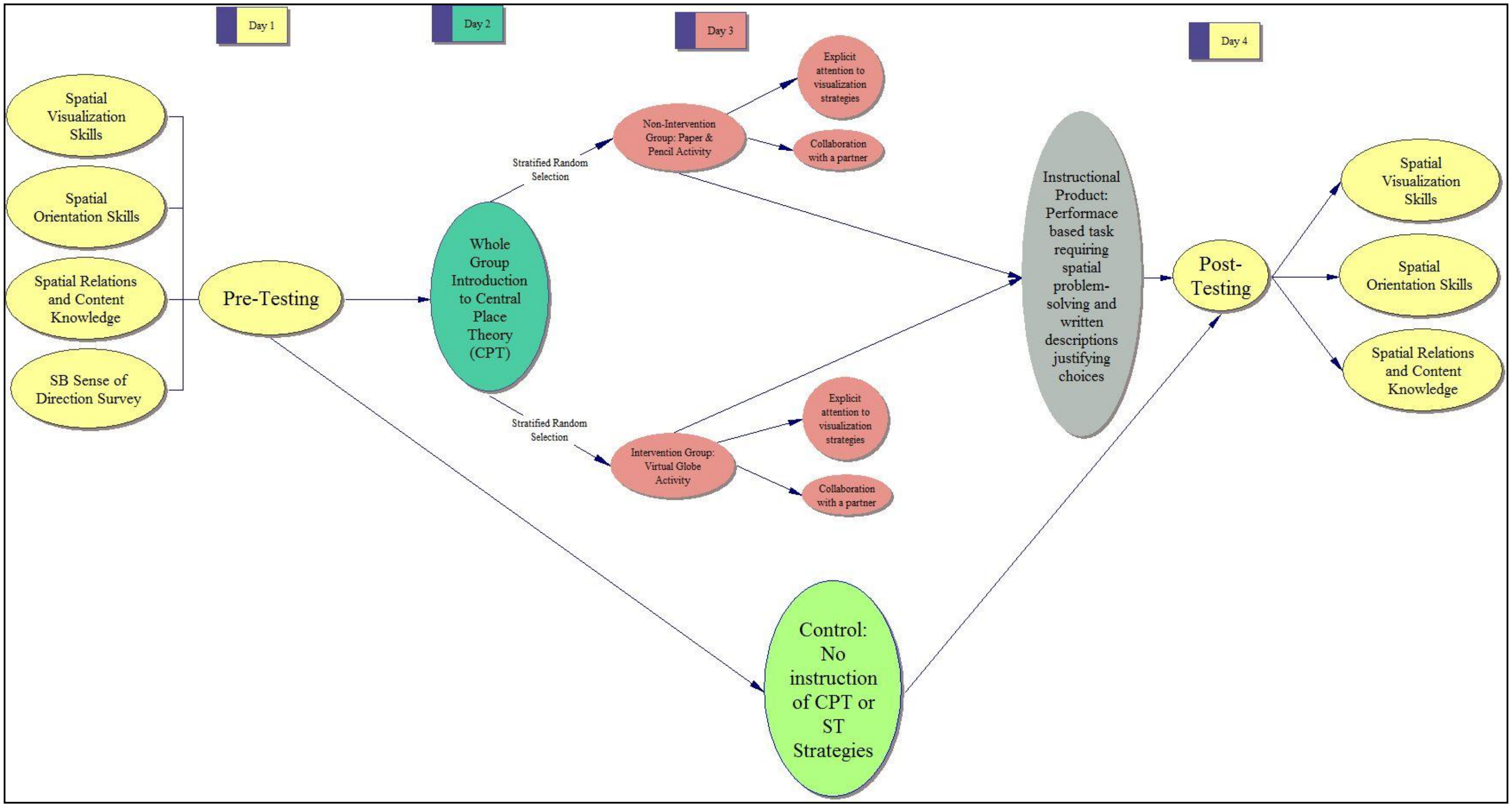


Figure 1. Study design. Day 1 was one week prior to Days 2 and 3. Days 2 and 3 were consecutive. Day 4 was 19 days after Day 3.

RESEARCH QUESTIONS

1. What is the effect of using GST as an instructional tool on changes to students' spatial thinking skills?
2. What is the effect of using GST as an instructional tool on changes in students' content knowledge of a spatial concept in geography?
3. What is the relationship among spatial skills, attitudes towards spatial and navigational abilities, and students' understanding of a spatial concept in geography?

OPERATIONAL DEFINITIONS

Spatial thinking is a broad term that incorporates spatial cognition and focuses on problem solving using spatial concepts, spatial representations, and spatial analysis. Spatial thinking requires the combination of three elements: concepts of space, tools of representation, and processes of reasoning (Committee on Support for Thinking Spatially 2006). Concepts of space include primitive spatial concepts such as location and complex spatial concepts such as pattern, diffusion, and gradient. Tools of representation include maps, graphs, models, charts, and images static or dynamic, tangible or digital. Reasoning processes include low-level cognitive skills such as recognizing, naming, or listing and high-level (output) skills such as predicting, hypothesizing, or imagining (Jo and Bednarz 2009).

Spatial cognition is an essential component of spatial thinking. It is the mental processes of thought used to imagine, interact with and communicate about space. It includes perception, memory, and recall of objects, persons, events, and ideas with spatial attributes, properties, categories, and relations. These mental processes are the basis from which we construct explicit, lexical, geometric, cartographic, and creative mental representations (Olson and Bialystok 1983). Development of spatial cognition can be affected by genetics, hormones, physiology, culture, and environment (Baenninger and Newcombe 1995; Casey 1996; Lloyd 2003). The interactions among these factors and the relative importance of each at different stages of cognitive development are unknown but current research is providing a better understanding.

Spatial skills are learned skills that can be taught, trained, and assessed. Consensus on different categories of spatial skills has not been reached. Most, however, typically include spatial visualization, mental rotation, spatial orientation, and wayfinding. Some of these skills, such as spatial visualization, have been reliably measured with various tests such as paper folding, embedded figures, and mental rotation tests. Spatial skills are related to spatial thinking but are more restrictive because different skills may be needed individually or in combination in order to think spatially (Lloyd 2003; Committee on Support for Thinking Spatially 2006, 26). Spatial thinking cannot be directly measured, but it is assumed that supporting spatial skills can be.

Geovisualization is an emerging field of inquiry that draws upon cartography, scientific visualization, image analysis, exploratory data analysis, cognitive psychology, and GIScience to produce theories, methods, and tools for the visual exploration, analysis, synthesis, and presentation of data that contains geographic information. “Geovisualization is about people, maps, process, and the acquisition of information and knowledge (Dykes, MacEachren, and Kraak 2005, 4).”

Geospatial technologies (GST) are technologies that facilitate geovisualization, characterization, mapping, wayfinding, or spatial analysis of features both concrete and conceptual on the Earth’s surface and subsurface. They include Geographic Information Systems (GIS), Remote Sensing (RS), Global Positioning System (GPS), and virtual globes such as Google Earth® and NASA’s World Wind®.

ASSUMPTIONS

Two primary assumptions guide this intervention study: 1) high ability in spatial skills is a predictor for success in learning spatial concepts, and 2) spatial thinking is malleable and can be improved through instruction and training. Therefore, the causal premise is explicit attention to spatial thinking strategies and practice integrated with geospatial technology and content instruction will lead to gains in students' spatial skills and content knowledge.

In addition, it is assumed that 1) the sampling method provides legitimate means for statistical comparisons between groups and among individuals within groups, 2) the instruments are valid for the variable measured and were administered with consistency among student groups, and 3) the students were motivated and participated in the testing and instruction at an equivalent level among groups and within groups from the start of the project to the end.

LIMITATIONS OF THE STUDY

Generalizations from this study are limited to 10^{th} grade students in honors world geography class. The study was limited by the length of exposure to the treatment. Changes in spatial skills may not be observed within such a short time frame. Multiple exposures over an extended period of time are more likely to produce change in spatial thinking skills.

The study may have been limited by the application of the instruments. The instruments used to measure spatial visualization and spatial orientation are not typically used to measure change from an instructional intervention. The instruments selected may not be appropriate for measuring *change* to students' spatial thinking skills. The instrument used to measure spatial relations content knowledge was developed specifically for this study. Reliability for the content test was not established. Therefore, the level of certainty with which research conclusions can be made is limited.

The study was limited by confounding variables that could not be controlled for. The use of virtual globes as an instructional tool may appear to be more effective because it is novel and student motivation may be greater in the intervention group than in the comparison group. Differences measured could be due to attitude differences between the two groups because each was aware that the other group was doing something "different." On the other hand, the intervention group might have been overwhelmed by the technology and lacked the time necessary to explore the spatial concept.

The study may have been limited by a researcher-as-teacher bias. The participation of the researcher as the class instructor may have introduced bias through an increase or decrease in student motivation and interest. Students may have viewed the activities as unimportant to their class performance or they may have been more motivated than usual due to the novelty of a different instructor and participation in a research project.

ORGANIZATION OF THE DISSERTATION

The primary purpose of Chapter I is to introduce the topic of spatial thinking, the objectives of the study, and the research questions. Setting, design, operational definitions, and study limitations were also introduced. Chapter II reviews literature relevant to the study. It provides the theoretical framework that grounded the study. It describes six factors that influence the development and improvement of spatial thinking. And, it proposes a conceptual framework that blends the six factors into a *Spatial Thinking Instructional Model* (STIM). The last section of Chapter II elaborates on one factor, mental images, as the primary focus of this study. In Chapter III, the research design, context, methods, and instruments used for this study are described in more detail. Chapter IV details the findings from the study. Last, Chapter V provides an analysis and interpretation of the findings informed by prior research. It includes a discussion of trends, inferences, and implications concluded from the results, and recommendations for future research and K-12 geography education.

CHAPTER II

LITERATURE REVIEW

INTRODUCTION

The purpose of this chapter is to review the literature on the characterization and development of spatial thinking and to identify areas of research that deserve more attention. The characterization of spatial thinking is controversial. Although no consensus exists, researchers agree that spatial thinking is a distinct cognitive ability separate from general intelligence (Brosnan 1998: Eliot 1987; Kyllonen and Gluck 2003; Thorndike 1921). The body of knowledge regarding when and how spatial thinking develops is growing, but no model to explain the development of spatial thinking is widely accepted. In fact, the question of nature versus nurture is revisited often in an effort to understand the roles innate ability and acquired skills play in the development of spatial cognition. Several competing psychological approaches attempt to explain human development of spatial thought: nativist approach, Piagetian approach, Vygotskyan approach, and interactionist approach. The current and most prevailing approach is Newcombe and Huttenlocher's (2003) interactionist framework based on a "bent twig" theory—innate ability plays a significant role in the development of spatial thinking but only through the interactions of experience, learning, and culture.

Spatial thinking is important for academic success in geography and other sciences, yet effective methods for explicitly teaching spatial thinking do not exist. Evidence of transfer from training in spatial skills to changes in the ability to understand

and solve discipline-specific spatial problems is scarce (for an exception see Talley 1973). Many have proposed using GIS to improve spatial skills and assert that using GIS improves students' spatial thinking (Committee on Support for Thinking Spatially 2006). Researchers have argued that the use of GIS helps students develop spatial abilities, solve spatial problems, reason spatially, and improve map reading skills (Lee and Bednarz 2009, p. 184) although little evidence exists to support these arguments (for an exception see Lee and Bednarz 2009).

Consensus exists concerning some topics: that high spatial thinking is positively correlated to success in geography and other sciences; that spatial thinking is an essential set of skills necessary for the development and application of GIS; that spatial thinking can be taught with training and/or direct instruction; that various human cognitive factors and life events contribute to the development of spatial thinking (e.g., spatial vocabulary, play experiences, memory capacity); and that sex differences (that can be minimized with training or instruction) exist for some types of spatial thinking and under certain conditions.

To understand the objectives and outcomes of this study, spatial thinking must be defined and described in order to compare applied studies or to adequately explain the outcomes of this study. Although this study does not propose a comprehensive definition of spatial thinking, it does define it operationally.

Effective research builds on prior knowledge. The topics for which a consensus exists provide the necessary foundation for assumptions made in this study. An important point of disagreement, and the focus of this study, is the assumption that use of GST increases students' spatial thinking which in turn improves their ability to understand discipline-specific spatial concepts.

Little research has been done on the relationship between spatial thinking training and the effect this training has on the ability to learn, understand, and apply discipline-specific spatial concepts, nor on the effect of using GST as an instructional and spatial thinking tool on discipline-specific, student, content learning. No connection between what is known regarding factors that contribute to the development of spatial thinking and a conceptual framework that accounts for these factors in relation to the teaching and learning of spatial thinking has been made. How do the various factors that contribute to the development of spatial thinking inform pedagogy for teaching geography? Some strategies and methods for teaching and learning of spatial thinking have been developed, but few, if any studies examine the impact of the instructional strategies on spatial thinking and discipline-specific content knowledge using ecologically valid empirical testing.

This chapter is structured in the following manner. Spatial thinking is described and characterized in five sub-sections. An operational definition is provided for spatial thinking and three spatial dimensions (or types of spatial thinking). Dominant approaches used to explain the development of spatial thinking are reviewed. Six "fluid factors" that influence the improvement of spatial thinking are identified: self-efficacy for spatial skills, metacognition, prior spatial thinking practice and play, spatial language, memory, and mental images. The six fluid factors are combined to create a conceptual framework, the *Spatial Thinking Instructional Model* (STIM).

Several fixed factors that should be considered but that are not included in the instructional model are sex, socioeconomic background, physiological differences, and cultural background. Educators should understand the potential sources of difference among students in spatial thinking. Traits associated with the fixed factors are determined at a young age (or at conception) and are not easily affected. The fluid factors, on the other hand, can be accentuated through education and practice to promote acquisition of spatial thinking at any age.

Of the six fluid factors, only mental images is investigated in this study, and, therefore, research on using GST as a visualization tool for facilitating students' creation of mental images is explored. The use of some technologies can profoundly change thought processes in addition to augmenting skills, referred to as *effects through* the use of technology (Salomon and Perkins 2005). It is argued that student use of GST has the potential to change the way mental images are formed, stored, and utilized (Uttal 2000) and that use of technology to create external visualizations can compensate for an inability to visualize structures and patterns internally (Hegarty et al. 2007) and thus enhance spatial thinking.

SPATIAL THINKING

Defining Spatial Thinking

Spatial thinking, as defined by the National Research Council's Committee on Support for Thinking Spatially, is a constructive combination of cognitive skills comprised of knowing concepts of space, using tools of representation, and applying processes of reasoning (Committee on Support for Thinking Spatially 2006, 12). Spatial thinking allows people to use space to model the world (real and theoretical) for structuring problems, finding answers, and expressing and communicating solutions. The inclusion of concepts of space makes spatial thinking unique (Committee on Support for Thinking Spatially 2006).

Concepts of space are declarative forms of knowledge that are the building blocks for spatial thinking. Concepts such as location, dimensionality, continuity, pattern, spatial association, network, and proximity are some examples of spatial concepts (Gersmehl and Gersmehl 2007; Golledge 2002; Janelle and Goodchild 2009; Lloyd, Patton and Cammack 1996).

Using tools of representation is necessary for competency in spatial thinking. Representations include maps, graphs, sketches, diagrams, flow charts, images, and models. Representations are used in a variety of modes (mental images, visual media, tactile, auditory, and kinesthetic) to identify, describe, explain, and communicate information about objects and their associated spatial concepts (Committee on Support for Thinking Spatially 2006).

Spatial thinking often necessitates complex reasoning (Jo and Bednarz 2009). Reasoning is the capacity of individuals to think, to make sense of the world, and to understand. Processes of reasoning are crucial for learning as individuals obtain, change, or justify practices, institutions and beliefs (Kompridis 2000). Processes of reasoning include low levels of thinking, such as recognizing, defining, and listing, and higher levels of thinking, such as evaluating, synthesizing, and generalizing (Jo and Bednarz 2009).

Spatial thinking is defined as a combination of these three components: spatial concepts, tools of representation, and processes of reasoning.

Following the National Research Council's (NRC) publication *Learning to Think Spatially* (LTS), there has been a general agreement on the definition of spatial thinking (Tsou and Yanow 2010; Kerski 2008; Bednarz and Lee 2011; Bednarz and Kemp 2011). Even with a commonly accepted definition, still very little is agreed upon regarding categories (or types) of spatial thinking, development of spatial thinking, or spatial thinking instructional strategies.

Types of Spatial Ability

Different dimensions of spatial ability have been propounded, and different methods have been used to distinguish them. Perhaps the most frequently used approach is to examine results from spatial ability tests using factor analysis. Two major types of spatial ability were identified early on and have been reliably substantiated: spatial visualization and spatial orientation (French 1951; Guilford, Fruchter, and Zimmerman 1952; Michael et al.1957; Thurstone 1950). Spatial visualization is characterized as the ability to mentally rotate, turn, twist, or invert one or more objects, or parts, of a configuration, that is, mental manipulation of an object or array of objects (Michael et al. 1957). Spatial orientation is characterized as the "ability to comprehend the nature of the arrangements of elements within a visual stimulus pattern primarily with respect to the examinee's body as the frame of reference, that is, mental manipulation of oneself" (Michael et al. 1957, 189).

Golledge and Stimson (1997) identify a third spatial ability, spatial relations, a more complex dimension that Golledge argues is the most geographical. Spatial relations includes recognition of spatial relationships, memory recall, abstract representations, and wayfinding.

Present-day psychologists endorse spatial visualization and spatial orientation as incontrovertible. Many psychologists also separate spatial abilities into two categories based on the frame of reference for the task, egocentric and allocentric. Egocentric spatial thinking specifies location and orientation of an object or array of objects by using one's body as the frame of reference (Ruggiero et al. 2010). An example of using an egocentric frame of reference is "the book is on the right side of the keyboard." Egocentric spatial thinking develops in infancy and is considered a precursor to allocentric spatial thought. Allocentric spatial thought "specifies location and orientation with respect to elements and features of the environment independently of the viewer's position" (Ruggiero et al. 2010, p. 51). Some researchers refer to this as a *geocentric* reference system with features such as the perceived direction of gravity, the Sun's azimuth, and Earth's magnetic field considered as coordinates for an environmental frame of reference (Dasen and Mishra 2010; McNamara, Rump, and Werner 2003). An *intrinsic* frame of reference, internal to the object or array of objects itself, is a third type considered important when categorizing spatial thinking (Mou and McNamara 2002). Hegarty and Waller (2004) argue that mental spatial transformations among these three spatial frames of reference (egocentric, geocentric, and intrinsic) constitute two main factors, or types, of spatial ability (Hegarty and Waller 2004, 176):

> The *spatial visualization* factor has been conceptualized as the ability to make object-based spatial transformations in which the positions of objects are moved with respect to an environmental frame of reference, but one's egocentric reference frame does not change. In contrast, the *spatial orientation* factor has been interpreted as the ability to make egocentric spatial transformations in which one's egocentric reference frame changes with respect to the environment, but the relation between object-based and environmental frames of reference does not change.

Linn and Peterson (1985), identified three types of spatial ability following a meta-analysis utilizing effect size comparison: spatial perception, mental rotation, and spatial visualization. These three are a poor match with those identified through factor analysis. Spatial visualization is defined by Linn and Peterson as "spatial ability tasks that involve complicated, multistep manipulations of spatially presented information" (Linn and Peterson 1985, p. 1484). Interestingly, they do not distinguish between mental manipulation of object and mental manipulation of oneself. Instead, spatial visualization is the catch-all category for higher-level processes of reasoning involving spatial concepts distinguished from spatial perception and mental rotation by the "possibility of multiple solution strategies." There is no mention in the meta-analysis of a spatial ability characterized by mental manipulation of oneself or from mental images of different egocentric perspectives.

Zacks et al. (1999) describe two spatial ability categories: object-based transformations, the ability to imagine a change in the position, orientation, or shape of an external object or array of objects, and egocentric perspective transformations, the ability to imagine one's position and orientation relative to the surrounding physical environment. These categories are identified by analyzing the results of spatial skills tests and functional magnetic resonance imaging (fMRI) of brain activity during testing. The fMRI imaging provides compelling evidence that the distinctions between these two cognitive processes are both behavioral and physiological. The spatial ability categories described by Zacks et al. are very similar to two of those described by Golledge and Stimson (1997), object-based transformation is analogous to spatial visualization and egocentric perspective transformation is analogous to spatial orientation.

The third spatial ability described by Golledge and Stimson, spatial relations, potentially requires both egocentric and object-based transformations utilizing both sides of the brain simultaneously. It is more complex because understanding and solving spatial-relation problems may require cross hemispheric thinking.

Spatial relations is indirectly defined by Golledge and Stimson as the ability to recognize, comprehend, and make associations/correlations of *relationships* and/or *patterns* among *different* spatially arranged objects. Golledge and Stimson state that it is the "least clearly defined" and the "catchall dimension". Lohman (1979) mentions the term spatial relations but does not define it. Lohman considers spatial relations less complex than spatial visualization. Rather than offer a definition or description, Lohman identifies psychological tests that he believes measures spatial relations (cards, flags, and figures). Linn and Peterson (1985) use the term spatial visualization in a very similar manner to Golledge and Stimson's spatial relations, both types are distinguished by higher-order processes of reasoning utilizing spatial concepts.

Another way to categorize spatial ability is on the scale of space perceived. Small-scale or "figural" space involves imagining or mentally transforming small shapes or manipulatable objects; large-scale or environmental space involves an integration of a sequence of views that change with a person's movement in the environment (Hegarty et al. 2006). A game board is an example of an object in small-scale space, and a parking lot is an example of large-scale space. But what distinguishes small-scale space from large-scale space and what difference does the distinction make to a person's spatial thinking?

Ittelson (1979) provides a useful way to categorize large-scale space by using the *surrounding quality*: "The quality of surrounding—the first, most obvious, and defining property [of large-scale space]—forces the observer to become a participant." The distinction between perception of an object in small-scale space and the environment in large-scale space is crucial. Objects in small-scale space require subjects to *observe* the object(s) where as one cannot simply be an observer of large-scale space; he must also be a participant (Ittelson 1979, p. 12). One can be surrounded by large-scale space but cannot be surrounded by small-scale space. When one moves—physically or mentally—through large-scale space (e.g., a parking lot, a room, a forest) his perspective constantly rotates and translates. Distance, direction, and topology between objects and the human in the environment change with one's movement (Rieser and Pick 2007). On the other hand, perception of an object or array of objects in small-scale space does not require movement—physical or mental—of the person or a change in the person's perspective. The object itself can be observed, moved, rotated or transformed independent of the observer's location or movement. Small-scale space typically involves the manipulation of *objects*. Large-scale space typically involves the manipulation of *self.* Spatial thinking in small-scale space most likely employs spatial visualization whereas spatial thinking in large-scale space employs spatial orientation.

This is not, however, a clear cut distinction. Map use blurs the distinctions between small-scale space and large-scale space. "Looking down on the earth allows us to see spatial information, such as the layout of an entire state, that can be almost impossible to perceive directly while navigating" (Uttal 2000, p. 247). Maps are objects contained in small-scale space. Intuitively maps are perceived using spatial visualization—manipulation of the object. Maps could, however, be perceived using spatial orientation—manipulation of self mentally moving through a two-dimensional representation changing orientation and view as one "moves" in the environment. Representations such as maps allow large-scale space to be perceived as a small-scale model. Conceptions of space are influenced by tools of representation such as maps (Uttal 2000). Conceptions of space are also influenced by the effectiveness of using tools of representation. Hegarty (2010, p. 285) found that visualization using interactive 3D computer images as a tool of representation depended on spatial intelligence for effective use of the tool causing individual differences in the ability to discover how to use the visualization tool. The type of spatial ability employed depends on the scale of the space, the tools of representation available, and the individual's ability to effectively use the representation.

In the 3D example above, users selected different strategies utilizing different spatial abilities to solve the same spatial task. Cognitive strategy selection is sometimes used to identify types of spatial ability. Considerable individual differences exist in the strategies selected when solving spatial tasks. Spatial abilities may not be used at all to complete an intuitively spatial task. Analytical or verbal strategies are sometimes employed to complete spatial tasks (Gluck and Fitting 2003). Schultz (1991) identified three strategic approaches used in five different spatial tests. "Move object" (imaginary manipulation of an object), "move self" (imaginary manipulation of one's own viewpoint), and "key feature" (analysis and manipulation of key features of the object) were the strategies used singularly or in combination in all five tests. "Key feature" is an analytical, non-spatial, strategy. As an example, in a Card Rotation test if a participant described his strategy as imagining the rotation of the card, it was labeled as "move object"; as moving his head, it was labeled "move self"; and as matching key features among the cards, it was labeled "key feature." Schultz found that "move object" was the most frequently used strategy but also found strategy variability in all tests.

Item difficulty and object complexity influence strategy selection for solving spatial tasks (Gluck and Fitting 2003). Kyllonen, Lohman, and Snow (1984) related strategy choice to the level of task difficulty. Participants would shift from a holistic—move object—strategy on easy spatial task items to an analytic strategy on more difficult items. These findings suggest that spatial thinking and success in solving spatial tasks varies among individuals not only because of differences in spatial abilities, but also differences in strategic approaches and the complexity or difficulty of the spatial task.

When different people use different strategies to solve the same spatial task and when people shift strategies within the same item or task, it becomes difficult to separate one spatial ability (category or dimension) from another. Strategy selection and performance on spatial tasks are associated (Cochran and Wheatley 1989; Hegarty and Kozhevnikov 1999; Schofield and Kirby 1994: Tzuriel and Egozi 2010), and therefore spatial strategy selection should be considered when exploring instructional methods for teaching and learning spatial thinking. In a study examining mental rotation, Freedman and Rovegno (1981) explained significant sex differences found in the Vandenbeg test of spatial rotation to be due to differences in cognitive strategy. All participants in the study reported using verbal strategies to solve spatial tasks, but high performing individuals—males and right-handed individuals—reported using visual strategies in addition to the verbal strategies. The Vandenberg test which is a timed test consistently yields differences in performance between males and females. Freedman and Rovegno found that as the difficulty of the spatial task increased, female performance decreased. They contributed this to the strategy used by females (Freedman and Rovegno 1981, p. 654).

> That sex differences in speed of reaction became larger as the degree of rotation between the figures increased suggested that females are slower at mental

> rotation. Performance speed may be related to sex differences in cognitive style, as verbal strategies are slower.

Flexibility of strategy selection is an additional factor to consider when examining types of spatial ability. “The best performers may be those who have a large repertoire of strategies and are able to select the best strategy based on characteristics of each task” (Gluck and Fitting 2003, p. 302). Cochran and Wheatley (1989) administered two spatial ability tests along with a spatial strategy questionnaire to 165 undergraduates. They found consistent differences in performance based on the spatial strategy utilized. High spatial performance in both sexes was related to the use of holistic/nonverbal strategies especially as the perceived difficulty of the spatial strategy increased. As an example, the visual strategy of visualizing a two-dimensional pattern as a three-dimensional object was perceived by the participants as difficult and self-identified use of this strategy was a significant predictor of performance on spatial ability tests. The implications of this study are compelling (Cochran and Whealtley 1989, p. 53):

> Although research shows only a correlation between spatial ability and logical processes (e.g., Linn & Kyllonen, 1984) and it is not certain that increasing spatial skills will result in an increase in problem-solving skills, this question is important and is obviously directly related to successful learning in a variety of content areas, especially science and mathematics.

Types of spatial ability have been identified in prior work through the five approaches summarized above: (1) factor analyses of results from different spatial ability tests; (2) identifying particular regions in the brain stimulated by different spatial tasks; (3) examining the effects of scale on the perception of space; (4) examining the influence of tools of representation on the perception of space; and (5) identifying strategies employed to solve spatial tasks of varying difficulty levels. None of these typologies in isolation are adequate. Instead, each approach complements the others and is compatible with the NRC Committee's on Support for Thinking Spatially definition of spatial thinking. The information gleaned from each categorization reveals a consistent pattern regarding identification of spatial abilities. Based on the similarities among the categories and patterns, three types of spatial ability are identified and operationalized.

Spatial Visualization

Spatial visualization is the ability to identify, recall, recognize, and/or mentally manipulate a two- or three-dimensional spatial image, object, or arrangement of objects from an object-based perspective.

Visualization is also, at a more difficult cognitive level, the ability to "mentally manipulate" (Golledge and Stimson 1997, p. 157) and recognize a spatial image, object, or arrangement of objects after some form of *transformation*. Transformation may include rotation, inversion, distortion, and/or conversion. Because mental manipulation of a transformed image requires identification, recall, and recognition; both identification and mental manipulation of an object(s) are examples of spatial visualization.

Spatial visualization is likely the primary visual strategy utilized for problems in small-scale space emphasizing a “move object” approach. It involves egocentric thought because the object or array of objects will likely be perceived in relation to one’s body as the frame of reference or by using the object’s internal frame of reference, rather than a geocentric frame of reference.

Spatial Orientation

Spatial orientation is “the ability to imagine how configurations of elements would appear from different perspectives” (Golledge and Stimson 1997, p.158). It requires spatial re-orientation with respect to one’s own body: mental movement of one’s self. The description for spatial orientation is the only term that is consistent in the literature (Lohman 1979, Lee 2005; Golledge and Stimson 1997). All typologies that include spatial orientation maintain that orientation is mental manipulation of oneself rather than mental movement of an object, image, or array of objects.

Orientation is likely the primary spatial problem-solving strategy for large-scale space emphasizing a “move self” approach. However, orientation is difficult to measure separate from visualization because spatial test items are solved with varying strategies. Spatial orientation will typically involve allocentric thought using a geocentric frame of reference that is independent of the viewer’s position. As the viewer changes position, or moves self, the frame of reference remains fixed even though the topology or spatial relations between the viewer and features in the large-scale space will change.

Spatial Relations

The operational definition for spatial relations is in agreement with some parts of Golledge and Stimson's description: specifically the ability to recognize, comprehend, and make associations/correlations of *relationships* and/or *patterns* among *different* spatially-arranged objects. However, simply identifying shapes, recalling layouts, or recognizing spatial patterns is insufficient to warrant the label of "relations."

The key words in Golledge and Stimson's description are *relationships* and/or *patterns* among *different* spatially arranged objects. This requires two or more "spatially arranged objects." To recognize a three-dimensional representation of an object in a rotated position is visualization, but to recognize patterns between two or more spatially arranged objects merits spatial relations. Spatial relations as described here is very similar to Linn and Peterson's (1985) definition of spatial visualization; spatial relations is a spatial ability requiring higher-level processes of reasoning which involve spatial concepts and the "possibility of multiple solution strategies."

Spatial relations requires spatial visualization, spatial orientation, or perhaps both as foundational spatial ability. Identifying spatial relation-type problems or tasks should exclude tasks requiring only input-level reasoning such as "identify" or "recall" (Jo and Bednarz 2009).

Identifying spatial relation problems, items, or tasks should focus on connections, associations, and correlations. Cognitive tasks suggested by Golledge and Stimson such as comprehending spatial hierarchies, regions, distance decay, and nearest neighbor effects could be appropriately labeled as spatial relations due to the emphasis on *analyzing* relationships and patterns to *understand* and *evaluate* spatially arranged objects. This is not to suggest that any level of reasoning above "knowledge" should be considered as spatial relations, but rather an argument that spatial relations problems require a competency in one or more of the other described spatial dimensions in addition to the spatial relations dimension.

A task or problem requiring spatial relations could be in small- or large-scale space. It could be in abstract or real-world space. It could be static or dynamic. It might require spatial visualization, spatial orientation, or both. Spatial relations does not stand separate from spatial visualization or spatial orientation. The key components of spatial relations tasks are a higher-level process of reasoning and an understandings spatial concept(s). Table 1 summarizes the characteristics of the three types of spatial ability.

Table 1. Comparison of the three types of spatial ability

	Frame of Reference	Scale of Space	Mental Manipulation	Optimal Strategy
Spatial Visualization	Egocentric or Intrinsic to the Object(s)	Small-scale	Of Object or Array of Objects (Object-based Transformation)	Move Object
Spatial Orientation	Allocentric/ Geocentric	Large-scale	Of Self (Egocentric Perspective Transformation)	Move Self
Spatial Relations	Transformations among Egocentric, Intrinsic, and/or Allocentric	Transformations between Small-scale and/or Large-scale	Of Object(s) and/or of Self	Strategy selection flexibility among move object, move self, and non-spatial (verbal & analytical)

APPROACHES TO THE DEVELOPMENT OF SPATIAL THINKING

In the previous section, spatial thinking was defined and three types of spatial abilities were described providing a shared understanding of key terms required to explain the design of this study. In addition to understanding what spatial thinking is, it is important to consider how spatial thinking develops. This understanding is especially important when planning instruction. Many theories hypothesize how spatial thinking develops (Allen 2003; Hart and Moore 1973; Kuipers 1978; MacEachren 1992;

Montello 1998; Newcombe and Learmonth 2005; Siegel and White 1975; van der Henst 1999). These theories can be categorized into four approaches: nativist, Piagetian, Vygotskyan, and interactionist (Kim, Bednarz, and Kim 2012).

Nativist Approach

One of the most important debates in the study of the development of spatial thinking is whether spatial abilities may be in some sense innate. The *nativist* argues that children are born with at least some types of spatial ability, and that even though the ability may develop with age and experience, there is a biologically determined starting point. Evidence for the nativist approach comes from studies with animals, young children and infants, and from map-use studies with the visually impaired (Carey and Xu 2001; Diamond 1991; Dyer and Dickinson 1996). Some of the most compelling evidence is from the apparent innate orientation abilities of animals.

Bees are able to communicate to other bees in their hive the direction and distance of a food source using the location of the sun as a reference. Dyer and Dickinson (1996) found working with bees, that bees deprived of exposure to the sun still, in some sense, assume that the light source exists and can predict its path across the sky from the east to the west. “Our experiments imply that bees are innately informed of the approximate dynamics of solar movement over the day” (Dyer and Dickenson 1996, p. 70). Blaser and Ginchansky (2012) found that both rats and humans were capable of selecting optimal routes the majority of the time in a navigational task using novel configurations—routes unfamiliar to the test subjects. This spatial ability which relies on metric cues of the object or environment is shared by humans and other species and is often referred to as the “geometric module” (Fodor 1983: Hermer and Spelke 1996). The similarities between the performance of the rats and humans support the possibility that both species rely on similar innate cognitive abilities to navigate.

Another area of active nativist debate is the study of what infants know about objects and spatial relations of objects. Using looking-time measures, researchers have found that infants just a few months old have considerable “initial knowledge” about spatial arrangements of objects (Scholl 2005). Infants seem to know that objects must follow a continuous path in space (Spelke et al., 1995); that objects will fall if unsupported (Needham and Baillargeon 1993); that one plus one equals two (Feigenson, Carey, and Spelke 2002; Wynn 1992); and that solid objects cannot occupy the same space (Spelke et al. 1992).

The nativist approach is often justified using an evolutionary argument. Spatial thinking evolved under real world problem-solving (i.e., hunting, foraging) and continues to be used in a similar fashion to solve similar tasks (i.e., grocery shopping, driving around a new town) (Blaser and Ginchansky 2012). Therefore, according to a nativist approach, spatial thinking is a cognitive skill humans are born with.

Piagetian Approach

The *Piagetian approach* proposes a sequential progression of understanding from topological space to projective and Euclidean space (Piaget and Inhelder 1967). Topological space is understood from an egocentric frame of reference. Children perceive objects and space in relation to themselves; the doll is near me, to the left of me, under me, etc. Contrary to the nativist approach which assumes an innate and initial understanding of straight lines, angles, distances, and plane figures (a Euclidean system of space), Piaget argued that “infants are born without knowledge of space, and without a conception of permanent objects which occupy and structure that space” (Newcombe and Huttenlocher 2000). Piaget and Inhelder (1967) found that children first understand space by taking notice of topological properties of objects and space rather than the metric properties.

As children mature, they start to understand space from a projective perspective and can imagine different viewpoints using an allocentric frame of reference. Once children make this egocentric-to-allocentric shift they begin to use landmarks and other features as a point of reference in order to conceptualize projective space. They understand that characteristics of the object or the environment have invariable characteristics: characteristics that remain unchanged even though they may appear differently when viewed from different distances or directions. Finally when thinking with Euclidean space, spatial relations are understood as a metric system of lines, axis, coordinates, angles, and distance. The individual develops a metric knowledge of the space using geometric properties of the object or space. Projective and Euclidian coding develop after topological and are not present at birth. One cannot understand projective or Euclidean space without first having mastered topological space. Projective and Euclidean space, however, were not developmentally sequenced in Piaget’s writing (Newcombe and Huttenlocher 2003). The egocentric-to-allocentric shift predicted by the

Piaget approach has inspired a large amount of research and cued the identification of spatial ability types such as spatial visualization and spatial orientation.

Evidence of the Piagetian approach can be found in research by developmental psychologists and geographers interested in spatial thinking. Downs and Liben (1991) found that college students struggle with geographic concepts such as map projections and coordinate systems because they have an incomplete mastery of projective space or Euclidean space (Downs and Liben 1991, 304).

> Instruction on map projections typically relies on reference to shadow projections, and yet significant numbers of college students fail to understand even the simplest cases of shadow projections. Instruction on coordinate systems assumes a Euclidean understanding of spatial relations, and yet many college students cannot represent the basic horizontal and vertical coordinates available in the everyday environment.

In contrast to Piaget and Inhelder's suggestion that children develop a non-egocentric frame of reference about the same time they enter the concrete operatory stage (approximately age ten), the college students in Downs and Liben's study had not yet progressed beyond a topological frame of reference: at least not in the realm of understanding map projection and coordinate systems. Discrepancy between the expected development and the actual is in the predicted age, not in the sequence. Downs and Liben argue for a Piagetian approach to geographic education—especially as it pertains to maps—because it allows a method for organizing many geographic concepts and it provides a goal for directing and evaluating curriculum for geographic education.

Thommen et al. (2010) found that children's map drawing ability progressed as predicted by Piaget from an egocentric perspective to an allocentric one. Maps of five-year-old children were confined to representation of simple topological relationships—a direct line between home and school. But as the participants aged, their maps increased in complexity and illustrated an allocentric or "decentered view" with more landmarks and abstract symbolic representations. Piaget and Inhelder (1967) previously identified the development of conceptual or representational space as the ability to conceptualize space through the understanding and use of symbols that represent spatial information. Thommen et al. confirmed that children's ability to use an allocentric frame of reference and symbols increases with age. Development of this ability is especially important for competency in spatial thinking and effective use of tools of representation specific to geography (e.g., maps).

Corresponding to the Piagetian approach, many geographers agree that survey knowledge of a specific area develops after landmark and route knowledge (Siegel and White 1975). Landmarks are physical structures or configurations that identify a specific geographic location; a building, a sign, an intersection, a tree, etc. A person's mental map of an area usually begins with landmarks. Landmarks are most likely perceived using a topological egocentric frame of reference.

Where landmark knowledge is visual and discrete, route knowledge is kinesthetic and interdependent based on movement among landmarks. Route knowledge is gained using a projective allocentric frame of reference. During travel or movement, a person may shift between topological and projective frames of reference, but to acquire and remember the route (especially as distance and complexity of the route increases) require constant updates of one's viewpoint among the different landmarks along the route.

Survey knowledge is a gestalt-like integrated spatial representation of a specific area or environment which develops as a result of extensive navigation or from map learning (Golledge, Dougherty, and Bell 1993; Shelton and McNamara 2004; Thorndyke and Hayes-Roth 1982). A person with survey knowledge of an area visualizes the space holistically as an arrangement of chunks rather than a series of sequential routes (Appleyard 1970). Survey knowledge is coded in Euclidean space using an allocentric frame of reference. Spatial relations among landmarks and routes are understood as an "incomplete" metric system of lines, axis, coordinates, angles, and distance. Survey knowledge develops after landmark and route knowledge, supporting the Piagetian approach to development of spatial thinking.

Survey knowledge is the most effective spatial representation for spatial reasoning and problem solving in large-scale space (Anderson and Leinhardt 2002). Map based instruction is the most effective method for gaining survey knowledge (Golledge et al. 1993), because it facilitates spatial thinking (Liben and Downs 2001; Liben et al. 2002; Uttal, Fisher, and Taylor 2006; Wigglesworth 2003).

Vygotskyan Approach

Both the nativist approach and the Piagetian approach minimize or ignore the social and cultural influences on humans' development of spatial thinking; neither approach provides a sufficient framework for understanding the role played by cultural tools such as language or maps. Those who take the *Vygotskyan approach* (or sociocultural approach) emphasize the effects of social and cultural influences on individual intellectual development and draw attention to examining how cultural tools affect this development (Gauvain 2008). The Piagetian approach suggests a chronological and linear development of spatial thinking. Even though the Vygotskyan approach distinguishes between elementary and higher-level mental functions, it does not assume a strictly chronological development of these cognitive abilities. Instead, the Vygotskyan approach assumes fluid dynamic development based on social interaction that creates a "mediational means for adapting basic cognitive abilities to higher cognitive functions" (Gauvain 2008, 411).

The Vygotskyan approach to the development of spatial thinking is bolstered by research examining the mediational and transforming influence of culturally diverse tools specifically: language, maps, and physical structure of the landscape. Research has demonstrated striking cultural differences in language used to describe frames of spatial reference, location, and direction (Levinson et al. 2002, 156):

> "…[N]oting that language is a human prerogative, suggests that the possession of language in general, and specific languages in particular, may reorganize and

> restructure the underlying cognition even in domains such as space that have been considered 'natural' and 'universal'. The role of language in restructuring thought may then account for some of the special properties of human thinking.

Levinson argues that a person's frame of spatial reference varies across cultures and that the external linguistic representations (i.e., language) used to describe space and spatial relations also predict nonlinguistic internal conceptual representations. Much of the evidence for the effects of language on spatial cognition has focused on comparisons between Western and non-Western cultures (Choi and McDonough 2007; Dasen and Mishra 2010; Nisbett 2004), but evidence also exists between developed and developing regions (Levinson et al. 2002) and among some Western countries (Hund, Schmettow, and Noordzij 2012).

Three frames of spatial reference identified by Levinson et al. (2002) are consistently used in cross-cultural studies of spatial thinking: (1) a *relative* frame of reference in which location of an object is described in terms of viewer-centered (egocentric) coordinates (e.g., place the fork to the left of the plate), (2) an *intrinsic* frame of reference in which location is described in terms of the object's or landmark's intrinsic coordinates or facets (e.g., the cat is in front of the chair), and (3) an *absolute* (also called geocentric) frame of reference in which location is described based on fixed bearings or cardinal directions from a reference point, landmark, or object (e.g., turn north at the bell tower). Some cultural groups describe location using only an absolute frame of reference, some using only a relative frame of reference, while others easily transition among all three (Levinson et al. 2002; Hund, Schmettow, and Noordzij 2012). Spatial language, it appears, is a proxy for the cognitive strategies used to mentally construct representations of space.

Maps are a cultural tool that provide a means to gain spatial information in a manner much different than spatial information gained through direct experience. Using and thinking with maps facilitates the acquisition of concepts of space and augments the ability to think about spatial relations (Uttal 2000). Uttal adopts a Vygotskyan approach to the development of spatial thinking when he argues that "maps can be construed as tools for thought in the domain of spatial cognition" (2000, 249). According to Uttal, map use can adapt and modify basic spatial abilities. Maps allow exploration of the world beyond immediate experience. Maps make information about relations among multiple locations visible in a single glance. Maps emphasize an abstract conception of space. And, maps "bring into view spatial and geographic information that would otherwise remain opaque or inaccessible from direct visual experience, and moreover they facilitate thinking about the represented information" (Uttal 2000, 250). Map use varies across cultures and among individuals within the same culture.

If maps truly influence the development of spatial thinking, then cultures that typically rely on maps and charts for navigation should differ in their concepts of large-scale space from those that do not. Evidence for this exists among persons of the Central Caroline Islands of Micronesia who navigate the open ocean in canoes (Hutchins 1995, p. 67) and among groups of aborigines in Australia who cross hundreds of miles of desert (Lewis 1976). Neither group uses maps or charts to navigate the huge expanse of space. Instead they have a deep knowledge of routes based on memorization of landmarks in which even the smallest feature is given significant and symbolic meaning. Without exposure to a map-influenced model of the world, they do not visualize the large-scale space in a survey-type representation and do not utilize an absolute frame of reference to determine location.

Even in cultures in which maps are frequently displayed and utilized, survey knowledge is difficult to acquire. Young children have difficulty forming a survey-like representation of an area they have had direct and prolonged experience exploring (Herman et al. 1985). When children are exposed to an overhead view or to a map, however, they are able to think about the space in absolute and survey-like terms improving accuracy and speed in spatial problem solving tasks (Reiser, Doxsey, McCarrell, and Brooks 1982).

In *Learning to Think Spatially* (2006) the definition for spatial thinking utilizes a Vygotskyan approach emphasizing tools of representation. These tools are seen as a *support system* for teaching and learning spatial thinking. The support system consisting of a combination of tools and pedagogy provides a mediational means for practicing spatial thinking in the classroom. The underlying belief is that instructional use of the tools—specifically GST—facilitates development of spatial thinking in a way that is more flexible and effective than instruction without them and can lower the age at which explicit training in spatial thinking can occur (The Committee on Support for Thinking Spatially 2006; Newcombe and Huttenlocher 2003).

Interactionist Approach

Lastly, the *interactionist approach* considers components of each of these three approaches as valid; newborn children likely arrive with a set of biologically determined innate spatial abilities as nativists argue, children and novices show predictable developmental transitions as a Piagetian approach would argue, and the influence of life experienced through culture and cultural tools is clearly evidenced in the variation of spatial thinking observed across individuals and cultures (Newcombe 2000). The interactionist approach considers the influence of both nature and nurture on the cognitive development of spatial thinking.

This research adopts an interactionist approach. Identifying this study's developmental approach is important. A nativist approach would provide no basis for instructional intervention. If spatial abilities are in place at birth and gains in those abilities are defined solely by age and genetics, not much should or could be taught. A Piagetian approach would be most interested in *when* to instruct the students in a particular spatial skill and less interested in the effectiveness of the instruction itself; the assumption being that if the students are developmentally ready, the instructional support provided or tools utilized would make little difference. A Vygotskyan approach is overly optimistic assuming anything can be taught at any time given the right environment, structure, and social influences (Bruner 1997). The interactionist approach recognizes that individuals have different starting points for spatial thinking, but these skills can be improved through training and scaffolding. Like rate of development, the effects of training may also vary based on individual differences in biology and environment. Adopting an interactionist approach grants the researcher flexibility to consider a wide range of studies from diverse disciplines, and it does not restrict the methods of research to a particular school of thought. In truth, most spatial thinking researchers are interactionists on a sliding scale. Some lean more towards a behavioral Piagetian approach and others more towards a socio-cultural Vygotskian approach. The important point is recognizing that students bring different spatial thinking strategies and preferences to the classroom. One student may visualize the world from an absolute frame of reference, another from a relative frame of reference, and a third a combination of all three. Regardless of students' initial spatial thinking skills, tools of representation paired with instruction can be used to enhance and develop multiple frames of reference and multiple strategies for spatial thinking.

FACTORS INFLUENCING THE DEVELOPMENT OF SPATIAL THINKING

Large individual differences in spatial thinking exist as a result of a complex combination of biological factors, socioeconomic factors, cognitive factors, affective factors, and education—formal and informal (Dasen and Mishra 2010; Levine et al. 2005). From an educator's perspective, not much can be done regarding biological or socioeconomic differences, but cognitive and affective factors that foster spatial thinking can be addressed in the classroom.

Six fluid factors that influence the development of spatial thinking have been identified from the literature. These factors are (1) self-efficacy for spatial skills, (2) metacognition, (3) prior spatial thinking practice and play, (4) spatial language, (5) memory, and (6) mental images. These factors are considered *fluid* because they can be altered through instruction. Fixed factors include sex, socioeconomic background, physiological differences, and cultural background (Levine et al. 2005; Maguire 2000). These factors are considered *fixed* because they are not affected by instruction.

Most of the fluid factors are a combination of affective and cognitive factors. It is very difficult to separate cognitive performance from self-beliefs, self-attitudes, and motivation (Mills 1991; Silvia and Sanders 2010). Therefore, instruction will aim at manipulating cognitive factors and enhancing affective factors. The sections that follow briefly describe each fluid factor and provide evidence to support the factor's influence on instruction of spatial thinking.

Self-Efficacy for Spatial Thinking

Self-efficacy is a measure of a person's own beliefs about his/her competency related to a specific skill set. It strongly influences perceptions of agency—the belief that personal actions or choices make a difference to the outcome of a situation or problem. A person's self-efficacy about the skills required for a given task, for example using a map to find a location in an unfamiliar city, will affect the decision to attempt the task and can often predict the likelihood of completion or success. Bandura (1977) hypothesizes that self-efficacy determines initiation of effort, amount of effort, and degree of persistence. Self-efficacy is derived from repeated success in accomplishing a task, indirect experience, verbal persuasion (e.g. self-talk, attaboys), and the physical condition of the body and its functions (Bandura 1977).

Self-efficacy for spatial thinking is positively correlated with success in performing spatially dependent tasks (Baker and White 2003; Cooke-Simpson and Voyer 2007; Hegarty et al., 2002; Lawton 1994; Linn and Peterson 1986, 93; Moe and Pazzaglia 2006). Few studies, however, have attempted to assess the instructional impact on spatial thinking by explicitly addressing the self-efficacy factor. Understanding how to foster self-efficacy is important because improving students' self-efficacy increases effort and persistence for spatial-dominant tasks and is likely to increase participation in geography and other spatially demanding sciences.

Moe and Pazzaglia (2006) went beyond establishing relationships and explored the impact of explicit instruction on self-efficacy by using verbal persuasion to manipulate the self-beliefs of 107 female and 90 male high school students. The authors divided participants into three groups: one group was told that men are better than women at mental rotation; one that women are better than men at mental rotation; and the third group was told nothing. The women in the "women are better" group and the men in the "men are better" group outgained their counterparts' pretest to posttest scores on the Mental Rotation Test (MRT) (Vandenberg and Kuse 1978). Likewise, women who were told they were less able than men and men who were told they were less able than women showed less gain and a significant decrease in performance on the MRT. Men and women in the group receiving no verbal manipulation had no significant change in pretest to posttest performance. The effects on mental rotation based on one episode of verbal persuasion were significant in this study for men and women.

Repeated intentional manipulation of students' self-efficacy for spatially dependent tasks should foster the development of spatial thinking.

Metacognition

Metacognition is thinking about one's own thinking (Nelson and Narens 1994). It focuses on self-monitoring and self-control of one's own thinking and learning. Metacognition has been of widespread interest in education research because of its connection to learning (Dunning, Johnson, Ehrlinger, and Kruger 2003; Georghiades 2000; Committee on Support for Thinking Spatially 2000; Pintrich 2002; Tanner 2012). Strategies for explicitly teaching metacognitive skills include using pre-assessments to encourage students to examine their thinking prior to a new topic, having students identify the Muddiest Point (Angelo and Cross 1993)—the point of most confusion—following a lecture or lesson, helping students recognize their own conceptual change, using reflective journals to encourage self-monitoring, integrating reflection as part of the course assignments, and modeling metacognitive skills by the teacher for the students (Tanner 2012).

In a study to determine if learning a route is automatic (innate) or effortful (learned), van Asselen, Fritschy, and Postma (2006) studied the influence of intentional versus incidental learning of a novel route. Thirty-nine undergraduate students were divided into two groups, an intentional group or an incidental group. Students in the intentional group were told to pay close attention to a route they would walk inside of a building because they would be asked to recall the route following the walk. The intentional group had been primed to think about their own thinking as they walked. Students in the incidental group were told a mistake had been made in the assignment of the test room and they would need to walk to another room. Five tasks followed the walk: recognizing landmarks from the walk; sequencing landmarks from the walk; tracing the route on a floor map of the building; physically re-walking the route from the end back to the beginning; and estimating the length of the route in meters. Participants in the intentional group performed significantly better than the incidental group on the map drawing task and on re-tracing the route in reverse, but there was no difference between the groups with respect to landmark recognition or landmark sequencing. The results of this study indicate that acquisition of survey knowledge, defined here as a Euclidean representation of space that includes distances, angles, and topology among landmarks, improves with intentional and effortful cognitive processing. Acquisition of landmark knowledge, on the other hand, depends largely on automatic or innate processing (van Asselen et al. 2006, 155).

The interactionist framework best explains the above results because both innate spatial skills and intentional training influenced the acquisition of spatial knowledge. The results also support the idea of a sequence of development from simple spatial concepts/skills (landmark recognition) to more complex spatial concepts/skills (mental imagination of a survey perspective) that require intentional self-monitoring of thoughts (Golledge, Dougherty, and Bell 1995). Incorporating metacognitive strategies into instruction facilitates the development of complex spatial thinking.

Prior Experiences (Informal and Formal)

Spatial thinking is to some extent socially mediated. Some individuals have more opportunity for participation in informal spatial activities than others. Experience, practice, or play involving spatial tasks improves spatial thinking (Baenninger and Newcombe 1989). Boys are more likely than girls to participate in spatially rich play, and they are given more freedom to wander away from home (Block 1978; Halpern 2000). Boys are encouraged more than girls to participate in math and science. This may increase boys' exposure to spatial tasks because of the spatial visualization skills utilized in these subjects (Sherman 1982). Boys are more likely than girls to participate informally in spatial activities through clubs (e.g., the Boy Scouts) that encourage outdoor navigational experiences such as surveying and orienteering (Gerber and Kwan 1994; Boy Scouts of America 2012). Differences in experiences between boys and girls have frequently been proposed as an explanation for differences in boys' and girls' scores on some psychometric tests for spatial ability. Differences in spatial experiences may also explain the dominance of males in spatially dependent careers, such as engineering (Caplan, MacPherson, and Tobin 1985; Linn and Peterson 1985; Newcombe 2010).

Prior informal spatial activity is related, although weakly, to spatial test performance (Baenninger and Newcombe 1989; Robert and Heroux 2004). This positive relationship has been documented with lego play, puzzle play, video gaming, and preference for "masculine toys" (Casey et al. 2008; Feng, Spence, and Pratt 2007; Levine et al. 2012; Sherman 1982; Tracy 1987).

Formal experiences through explicit training improve spatial thinking. Formal practice solving spatial puzzles, practice pairing graphed images with stacked cubes, instruction about strategies for spatial problem solving, coursework in disciplines where spatial information is a critical component, and long-term practice on specific spatial test items are associated with gains in spatial thinking (Jones and Burnett 2006; Ben-Chaim, Lappan, and Houang 1988; Tzuriel and Egozi 2010; Schofield and Kirby 1994, Lee and Bednarz 2009; Wright et al. 2008; Sorby 2009). Baenninger and Newcombe (1989) conducted a meta-analysis examining the influence of training on spatial thinking and identified four significant influences of formal experiences on spatial test performance: short training periods have a similar effect size on spatial thinking as repeated practice sessions; training should be of a medium time duration; task-specific training is better than general training; and no significant sex related differences in training effects exist. They concluded that formal experiences with spatial training produce a strong although task-specific improvement in spatial test scores.

Prior formal and informal experiences foster gains in spatial thinking. Informal experiences are positively correlated to higher spatial test scores. The magnitude of the difference is small, but the gains occur across a variety of spatial test items—the effect is generalized to multiple spatial tasks. Formal spatial training experiences are strongly correlated with higher spatial test scores. The magnitude of change is large, but the influence is narrow—the effect is specific to the spatial skill instructed or practiced. Formal instruction of spatial skills and strategies in the classroom paired with informal experiences employing the skills and strategies through field work, applied homework, and field trips are recommended for the effective instruction of spatial thinking in geography and other spatially rich sciences.

Spatial Language

Spatial thinking is advanced by the acquisition of spatial language (Pyers et al. 2010). Language plays a significant role in structuring cross-cultural differences in spatial thinking (Levinson et al. 2002; Majid et al. 2004). Furthermore, variations in the frequency of spatial vocabulary use among same-language individuals foster differences in spatial thinking (Pruden, Levine, and Huttenlocher 2011). Spatial language and spatial thinking covary with age and across languages. The direction of this causal relationship, however, is difficult to determine and has been debated for some time.

Theories about how language affects thought range from a deterministic approach, that is, all thought is defined by language (Whorf 2012) to the opposite extreme, language does not influence thought at all. An intermediate view supported by recent evidence is that spatial language augments the ability to think spatially: the use of spatial language has the capacity to change the way people perceive and conceptualize the world (Gentner and Lowenstein 2002). Spatial language can be used as a tool to transcend cognitive limits allowing acquisition of spatial skills at a developmentally earlier age than would otherwise be possible (Hermer-Vasquez, Moffet, and Munkholm 2001). Spatial language varies by linguistic group while spatial vocabulary varies within linguistic group. Both language and vocabulary play a critical role in the development and instruction of spatial thinking.

The language one speaks shapes the way one understands the world. Dasen and Mishra (2010) found in a cross-linguistic study that some cultures do not have words to express an egocentric frame of reference (in particular, hunting and gathering societies in Australia and in the Kalahari Desert of Southern Africa). Other cultures, however, use egocentric vocabulary exclusively never using geocentric vocabulary (such as Geneva). Dasen and Mishra interpret these differences as a cognitive style choice rather than a cognitive limitation. In other words, it is not that the individuals are incapable of understanding an egocentric or geocentric frame of reference, only that vocabulary provided by the culturally bound spatial language defines the habitual means of thought and communication about spatial concepts and relations.

The frequency of spatial verbalizations (e.g., big, tall, bent, edge, circular, dense, etc.) varies considerably among individuals of the same linguistic group. Some use many spatial terms to communicate and others use practically none. More frequent use of spatial vocabulary by parents results in more spatial vocabulary use by their children, and children who produce more spatial vocabulary at a young age are more likely to become better spatial problem solvers at a later age (Pruden et al. 2011). Spatial vocabulary used within a classroom by the teacher also influences the frequency and accuracy of spatial terms used by the students (Bednarz, Bednarz, and Metoyer 2009).

Spatial language strongly influences the early development of spatial thinking. As a result, students arrive in the classroom with a broad range of vocabulary (spatial and non-spatial) to describe phenomena and to solve problems. The intentional integration of spatial vocabulary in instruction can increase students' understanding of spatial concepts and improve their spatial problem-solving skills.

Memory

Thinking about space and spatial relations requires memory. Although humans can store durable mental representations over long periods of time, they also utilize a form of memory that can create and manipulate mental representations rapidly and on the fly (Moher, Tuerk, and Feigson 2012). Working memory, which handles the temporary storage of information, serves this role. The working memory utilized in spatial processes, such as wayfinding, is not a generic cognitive function, but a specific function of visuo-spatial working memory (VSWM) (Garden, Cornoldi, and Logie 2002).

Differences in VSWM can account for some differences in spatial thinking. High-spatial and low-spatial individuals differ in the quality of the mental spatial representation they create and in their ability to maintain the representation after mentally transforming the representation (Hegarty and Waller 2005). The more complex the image, the more difficulties low-spatial individuals have maintaining the image in memory. For example, low-spatial individuals often forget or drop information about a letter on one side of a cube once that side is rotated out of their view (see an example of a cube comparison task in Chapter 3) (Carpenter and Just 1986). Some individuals require multiple attempts when rotating Shepard-Metzler figures suggesting they forget the figure's details as they attempt to rotate it (Carpenter and Just 1986). Differences in spatial thinking are related to differences in working memory resources for storing and processing of spatial information: “In this view, a high-spatial individual might have more resources for storing and processing spatial information than a low-spatial individual” (Hegarty and Waller 2005, 141).

Females have demonstrated a lower VSWM capacity than males in many studies (Halpern 2000; Garden et al. 2002; Lawton and Morrin 1999). Kaufman (2007) demonstrates that sex differences in spatial visualization can be accounted for by differences in VSWM capacity. These differences are particularly marked in complex tasks involving elaboration, integration, and transformation of visuo-spatial material (Vecchi and Girelli 1999). According to Thorndyke and Hayes-Roth (1982), a real-world spatial task requires less VSWM load than a simulated task. Females often perform worse than males on simulated spatial orientation tasks but perform similarly on real-world orientation tasks (Rossano and Moak 1998). Ward, Newcombe, and Overton (1986) found no gender differences between males and females in an orientation task when a map was present (low VSWM load), whereas males outperformed females on the same task when the map was absent (high VSWM load).

Working memory capacity for visuo-spatial information can be increased, potentially improving spatial thinking performance in general (Klingberg 2010; Morrison and Chein 2011; Shipstead, Redick, and Engle 2012). Strategies for increasing students’ VSWM capacity include chunking complex visual images, reducing spatial anxiety, using heuristic visualization, and using intentional mental imagery (Tzuriel and Egozi 2010; Moher et al. 2012; Shipley 2009). Visuo-spatial working memory plays an important, albeit indirect, role in developing competency in spatial thinking; the cognitive load for VSWM varies among individuals and between groups; and an individual's capacity for storing mental spatial representations in VSWM can be improved through instructional strategies.

Mental Images

Much of thinking is accomplished by recalling and manipulating perceptual and motor experiences through internal mental imagery, rather than through internal verbalization. Cognitive abilities depend on a complex combination of images and words, but the ability to comprehend, remember, reason, and solve problems from images develops prior to the ability to do the same with words. The importance of using mental imagery to think may seem obvious, yet by the time a child begins first grade—the typical start of formal education—thinking verbally is the dominant focus of instruction. Instruction utilizing mental imagery, if present at all, is accidental and hidden (Reed 2010). Dual-encoding theory can be used to understand the significance of learning verbally and spatially (graphically) concurrently. Spatial thinking allows high spatial learners to devote more cognitive resources to building *referential* connections between verbal and visual representations when the information is presented concurrently. Low spatial thinkers, on the other hand, struggle with making referential connections. This may be due to cognitive overload caused by trying to process verbal and spatial representations at the same time (Mayer and Sims 1994).

Just as it is necessary to learn the alphabet prior to learning how to read, practice in storing, recalling, and manipulating mental images is necessary for the development of complex spatial thought. Spatial thinking builds from multiple skill sets gained through experiences using mental images. These skills develop early and prior to verbal skills. Some of these skills include the ability to perceive and recall visual patterns and image schemas (Fantz 1961), the ability to acquire global concepts (such as the concept of *containment*) by generalizing from multiple stored images (Mandler and McDonough 1996), the ability to sequence temporal events through imagery (Hegarty, Kris, and Cate 2003), and the ability to comprehend mathematics through imagery (for example mathematical understanding through use of a *mental number line*) (Dehaene 1997; Hegarty and Kozhevnikov 1999).

Close links exist among space, time, and mathematical reasoning. Mental imagery is a cognitive non-verbal tool used to understand these concepts and their interconnections. Mental imagery without language, however, would constrain an individual in regards to the development of spatial thinking. Practicing the storage, recall, and manipulation of mental images to facilitate spatial thinking should not replace verbal thinking instruction, but it should be an intentional and explicit objective of instruction.

Evidence from prior studies indicates that intentional use of tools for visualization improves students' ability to form mental images and mental schema of spatial concepts in geography and other sciences (Sanchez and Wiley 2010; Gilmartin 1986). The use of static visualization tools such as charts, maps, and diagrams has been shown to enhance science learning (Gilmartin 1986; Mayer et al. 1996). The use of dynamic animations and video has also been shown to facilitate learning in science (Yarden and Yarden 2010). Integrating appropriate visualizations may support the creation of mental images and facilitate spatial thinking, especially for individuals with lower spatial ability who have difficulty constructing mental images without the aid of visualizations (Sanchez and Wiley 2010).

The use of visualizations, however, does not always result in improved learning for all students under all conditions, and can even hinder learning (Hoffler, Prechtl, and Nerdel 2010; Schnotz and Rasch 2005). The influence of students' learning preference, cognitive style, prior experiences, and initial spatial thinking ability play a role in the effectiveness of using visualization tools to create and employ mental images (Mayer and Massa 2003). Studies exploring the effects of explicit training in mental imagery strategy, however, demonstrate that training especially benefits individuals with lower spatial ability indicating that spatial ability can be improved by learning imagery strategy (Gyselinck 2009 et al.; Meneghetti et al. 2013).

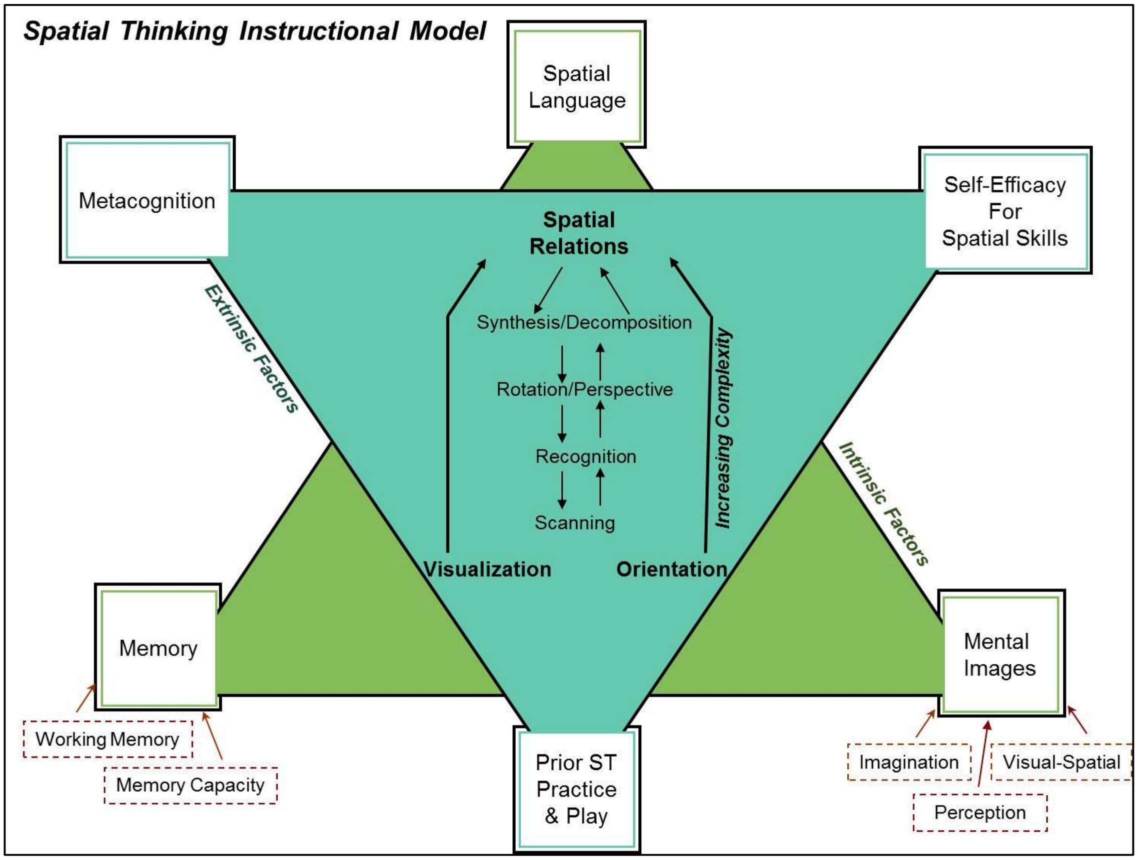
One tool of representation that could be used in the K-12 curriculum to encourage mental imagery and facilitate spatial thinking is GIS (Committee on Support for Thinking Spatially 2006). GIS is an integrated system of hardware and software designed to allow the user to manage, manipulate, visualize, and analyze spatial information. GIS is a dynamic, digital, and interactive tool used to model and solve real world problems. Little is understood, however, about how using GIS as an instructional tool affects the spatial thinking of diverse groups of students, nor how its use influences students' understanding of a spatial concept. According to Meneghetti et al. (2013), individuals with lower spatial ability should benefit most from using GIS. On the other hand, because of interference effects and cognitive overload that may occur from having to learn the technology simultaneously with the mental imagery strategies, individuals with lower spatial ability may benefit more from static simpler tools, such as paper maps (Bunch and Lloyd 2006; Rossano and Moak 1998). The question of who learns best with what type of tool is important for determining appropriate use of GIS in the classroom.

Mental imagery is necessary for competent spatial thinking. Tools of representation enable and facilitate mental imagery. Geospatial technologies, specifically GIS, are dynamic and interactive visualization tools that are thought to promote the creation and use of mental images and thus facilitate spatial thinking, especially by individuals of lower spatial ability. The question of who learns best with what type of tool, however, has not been examined in an authentic educational setting, and the answer to this question is important for determining appropriate use of GST in the classroom.

THE SPATIAL THINKING INSTRUCTIONAL MODEL (STIM)

The fluid factors, individually and collectively, strongly influence spatial thinking competency. Explicit attention to strategies for utilizing and improving performance on each of the factors has the potential to enhance spatial thinking. These factors, (1) self-efficacy for spatial skills, (2) metacognition, (3) prior spatial thinking practice and play, (4) spatial language, (5) memory, and (6) mental images, have been incorporated into a *Spatial Thinking Instructional Model* (STIM) to provide a conceptual framework illustrating how the factors interact (Figure 2).

Figure 2: The Spatial Thinking Instructional Model (STIM)



Three of the factors are *intrinsic*: memory, spatial language, and mental images. These three are considered intrinsic because they develop automatically as a central and innate part of human cognition. A human infant perceives mental images without having to learn the skill. An infant's brain is wired to create and maintain images in memory without prior experience or training. Spatial language is automatically acquired as an infant listens to and mimics other humans' language and vocabulary. One is not born with a vocabulary but with the innate capacity to acquire language. This is not to say the intrinsic factors do not advance with age, that they are not influenced by the sociocultural context, or that they cannot be improved through practice and instruction. Rather, intrinsic means these factors are present at birth regardless of sex, socioeconomic status, culture, level of intelligence, physical limitations (e.g., congenitally blind), or prior experiences.

The other three factors are *extrinsic*: prior formal and informal experiences (practice and play) with spatial thinking, metacognition, and self-efficacy for spatial skills. These are considered extrinsic because they are derived from the intrinsic factors, are gained after birth from experiences and beliefs, and are learned through a sociocultural context. The triad containing the extrinsic factors is superimposed on the triad with the intrinsic factors illustrating that the second triad is derived from and follows the first (or bottom) triad in the figure. This arrangement does not suggest that influence between the triads flows in only one direction, instead that the intrinsic factors are the foundation. Both categories of factors can be improved upon through practice and instruction.

The six factors identified as strongly affecting competency for spatial thinking, could also be used to understand competency in cognitive domains other than spatial thinking. Numeracy, for example, is a cognitive domain in which the influence of self-efficacy has been shown to impact achievement in mathematics (Ross, Bruce, and Scott 2012). Several studies of literacy, another cognitive domain, report the positive effects of metacognition on understanding text (Wilson and Smetana 2011). The primary difference for the STIM is the emphasis on *spatial*: spatial language, visuospatial memory, experiences using spatial thinking to play or to solve problems, and self-efficacy for spatial skills. It is also a conceptual framework intended to identify areas for intervention through instruction. Building on prior work is crucial for designing an intervention that has a good probability—based on evidence—for improving students' spatial thinking and content learning.

At the center of the STIM figure are the three cognitive foundational spatial abilities described previously in this chapter: spatial visualization, spatial orientation, and spatial relations. Visualization and orientation are listed parallel to each other in the bottom corners of the figure's center. The parallel placement indicates the equal but independent nature of the two abilities. Recall that visualization typically utilizes an intrinsic or egocentric frame of reference in small-scale space for object-based transformations. Orientation, on the other hand, utilizes an allocentric or geocentric frame of reference in large-scale space for egocentric perspective transformations.

Spatial relations is placed above visualization and orientation in the figure's center indicating spatial relations is the more complex spatial ability. Spatial relations requires use of visualization, orientation, or a combination of both. The level of complexity increases as the mental object or schema is manipulated to greater degrees. The double arrows in the figure indicate that tasks can transition among lower level processes and higher level processes without necessarily a linear or step-wise fashion (Metoyer 2008). As an example, in an embedded figures task, a person could use only visualization to scan and recognize triangles. If, however, he were asked to determine the number of equilateral triangles that could be constructed by mentally breaking down the individual line segments presented in the figure and assembling them into triangles, he would use a more complex form of visualization along with "*analyzing* relationships and patterns to *understand* and *evaluate* spatially arranged objects"—spatial relations.

The STIM illustrates how the six fluid factors interact to influence development of the foundational spatial abilities. Higher competency levels with spatial abilities improve success with spatial thinking in general. The STIM allows one to consider mechanisms and instructional strategies that affect differences in spatial thinking. The following section outlines *why* instruction in spatial thinking is important to academic success, especially in geography and other spatially dependent disciplines.

JUSTIFICATION FOR TEACHING SPATIAL THINKING IN THE SCIENCES

Even if educators are aware of spatial thinking and its relationship to scientific literacy, they often retain a misconception that spatial thinking is an innate set of abilities that cannot be improved. Existing curricula include no time for attention to an additional skill set. For the educator who recognizes the importance and feasibility of teaching spatial thinking, there are few, if any, resources for the educator to draw from. As a result, teaching spatial thinking is not considered, assumed to be fixed and unchangeable, or ignored because the resources and tools needed to train and teach spatial thinking in a classroom context are not available. Geospatial technologies have been promoted as ideal tools to address these resource and pedagogical issues.

GST EDUCATION

Several studies have shown promise linking the use of GST, specifically GIS, to spatial thinking and spatial concepts in a class setting. Geospatial technologies are a super set of technologies that includes the ability for data capture, data storage, data management, data interpretation, data integration, and communication to an end consumer of information focusing on geographic, temporal, or spatial context (DiBiase et al. 2010). Geospatial technologies include GIS, global positioning systems (GPS), navigation systems, remote sensing technologies, virtual globes (such as Google Earth, NASA WorldWind, ESRI ArcExplorer), web-based GIS, and mobile GIS that allow 2D and 3D visualizations of the earth.

For the purpose of this study, the intervention focused on the established relationship between the development of spatial thinking and the use of maps both in static and digital formats. Maps are a common and useful tool for understanding geographic concepts. Maps, in the broadest sense, can include mental maps, conceptual frameworks, or flowcharts. But in this study, prototypical maps are limited to views of earth from an aerial perspective as you might see on a road map, in an atlas (Liben and Downs 1993), or as a digital display in a GIS.

Maps can be used to display or communicate information such as soil composition of a given region, transportation networks, cultural boundaries, weather patterns, etc. However, they can also be used to "think with space [which] involves thinking with or through the medium of space in the abstract." (Committee on Support for Thinking Spatially 2006, 30). Thinking "with space" is exemplified in geographic examples such as modeling climate change, imagining earth-sun interactions to understand earth's seasons, or analyzing spatial information needed to plan the best location for a new solid waste facility. Map use can facilitate the development of spatial cognition (Liben et al. 2002; Lobben 2004; Uttal 2000). Maps, used as tools for representation, facilitate the construction of mental images which fosters spatial thinking. More specifically, GST, such as GIS and Google Earth, can be utilized in the classroom as appropriate visualization tools to facilitate spatial thinking and support content learning (Committee on Support for Thinking Spatially 2006; Kerski 2008).

SUMMARY

An operational definition of spatial thinking has been provided. Three types of spatial ability have been identified and described. Four approaches for understanding the development of spatial thinking have been explored and the interactionist approach identified as the approach utilized in this study. Six fluid factors were identified as instructional factors. These factors were identified because they are malleable in a classroom setting, and they influence development of spatial thinking. These factors, (1) self-efficacy for spatial skills, (2) metacognition, (3) prior spatial thinking practice and play, (4) spatial language, (5) memory, and (6) mental images, were incorporated into the *Spatial Thinking Instructional Model* (STIM). Mental images, facilitated by the use of GST as a visualization tool, was the primary focus of this study.

After outlining the terms, approaches, and the conceptual model, evidence supporting the inclusion of spatial thinking instruction in the sciences was provided. Main points of this argument are that 1) high spatial thinking is positively and significantly related to academic and career success in the sciences, 2) spatial thinking is malleable and individual gains in spatial thinking can be made through training or education, and 3) gains in spatial thinking show considerable promise for affecting gains in understanding spatial concepts.

Finally, focusing on the mental images factor, GST was described as an instructional tool to facilitate the creation and manipulation of mental images. This could, in turn, foster gains in spatial thinking. The intervention used in this study incorporates the theoretical foundation of how spatial thinking may be improved through intentional and explicit instruction, the use of GST as an appropriate tool for support, and effective pedagogical strategies to enhance both spatial thinking and geographic content knowledge.

CHAPTER III

METHODOLOGY

A two-day instructional unit focused on teaching central place theory was developed as an intervention for this study in order to understand the impact GST have on students' spatial thinking and on their understanding of a geographic concept. The primary purpose of the intervention was to provide students with 1) instruction on central place theory explicitly focusing on spatial thinking strategies and 2) intentional practice with spatial thinking through the use of GST.

Four assessments were used to examine students' spatial thinking, content knowledge, and self-reported navigational skills: a spatial-visualization skills test, a spatial-orientation skills test, a spatial-relations content knowledge test, and the Santa Barbara sense of direction (SBSOD) questionnaire. Classroom observations by two third-party observers and by the researcher were utilized to inform a qualitative description of the instructional unit and intervention. This chapter describes the research design, methods of data collection, assessment tools, and methods of data analysis.

RESEARCH DESIGN

A quasi-experimental intervention design was conducted in a field setting with the intent of having an instructional impact. It was, in part, a development study because the instructional unit was developed and delivered to a sample of high school geography students by the researcher as part of the research process. The effect of the instructional unit was explored by comparing pre and posttests among three groups: an intervention group, a comparison group, and a control group. All three groups completed pre and posttests. The intervention and comparison group received an introduction to central place theory on day one of the unit using a formatted structure of guided inquiry and direct instruction. On day two, the intervention group completed an activity using GST to test the premises of central place theory. The comparison group, also on day two of the unit, completed an activity similar to the intervention group using traditional paper-and-pencil maps, data tables, and rulers rather than digital maps provided through GST.

A sequential explanatory strategy was utilized for the research design with priority on quantitative data collected using a repeated measures format. Qualitative data were collected to assist in post hoc interpretation of the quantitative findings. Qualitative sources of information included observations by third-party geography experts during the implementation phase, reflections by the classroom teachers, and observations of the researcher.

SETTING AND SAMPLE

The study was set in a Texas urban public high school, A&M Consolidated High School in College Station Independent School District. Permissions to conduct the research were secured from Texas A&M's Institutional Review Board and from the school district following a research application process and committee review. The classes recruited for the study were five grade 10 world geography honor classes. Student participation within these classes was solicited and participation was acknowledged with a five-dollar gift certificate to a local vendor.

Three of the five honor classes were taught by one teacher, and two classes by a second teacher. Both teachers had several years of experience teaching honor-level geography and were recognized as excellent teachers by the school district.

Each class had approximately 23 students with relatively equal numbers of males and females. One class (n = 20) was reserved as a control class where no instruction on spatial thinking strategies or content related to central place theory was presented. Figure 3 illustrates the sampling design in which the remaining students (n = 80) were divided into the four treatment classes by sex then randomly assigned to either the intervention group (using digital maps and GST) or the comparison group (non-digital paper-and-pencil maps). Stratified random sampling insured equal gender representation by class period in the two groups. Final student numbers varied from beginning numbers as a result of attrition caused by absences during portions of the activity or during the posttesting (Table 2). At the end of the study, one hundred high school students participated in the full study: 48 females and 52 males.

All three groups completed the pre/posttests of spatial visualization skills, spatial orientation skills, and spatial relations content knowledge tests. One class acting as the control group received normally scheduled instruction as determined by their classroom teacher. The remaining four divided classes participated in a guided exploratory instructional unit on central place theory using either virtual globe and digital maps or traditional paper-and-pencil maps. Both the intervention and comparison groups received explicit instruction during the activity for using visualization strategies to enhance their use of the respective tools.

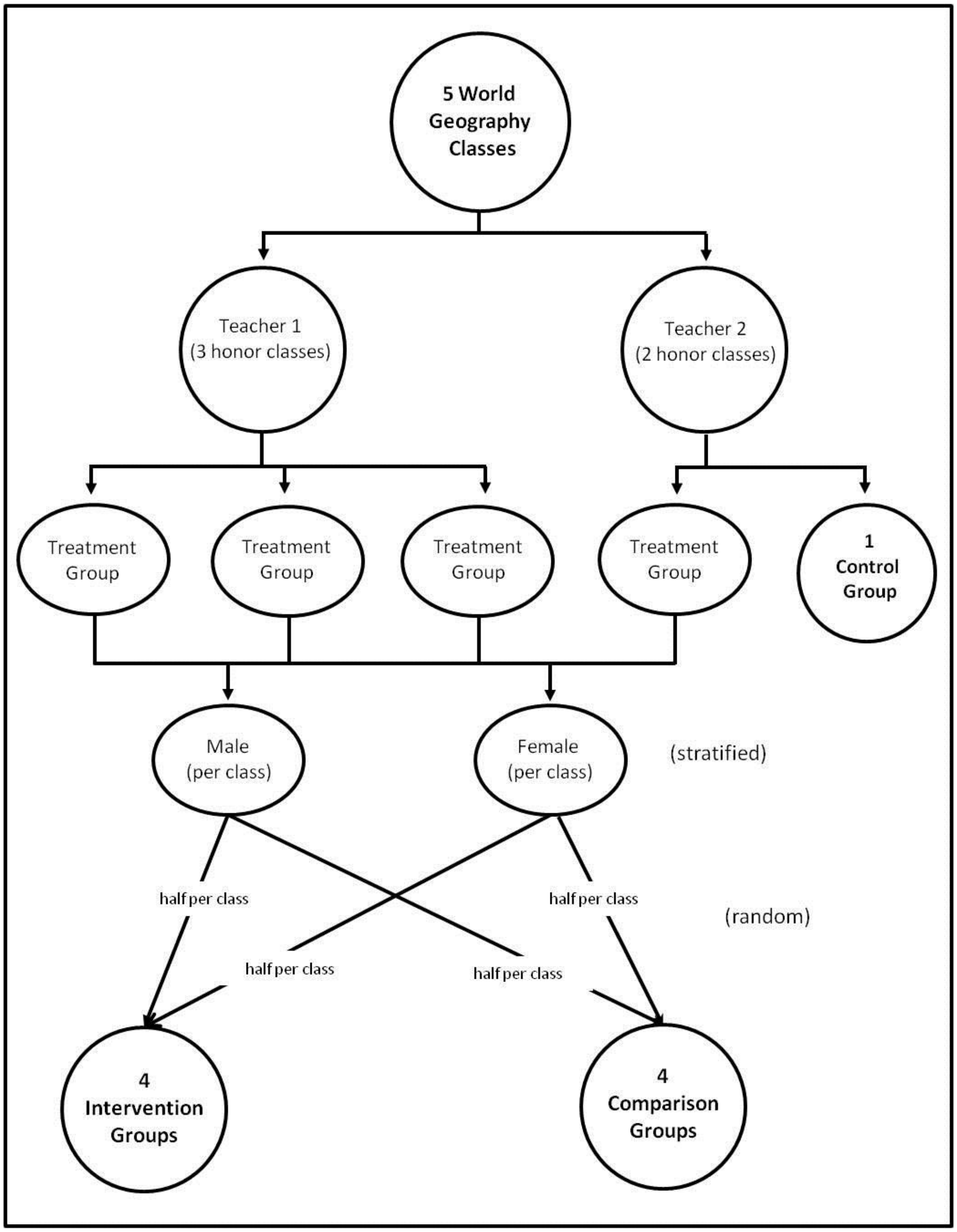


Figure 3. Sampling Design. Four world regional geography honor-level classes were split into an intervention group (n=40) and a comparison group (n=40). One world regional geography honor-level class was reserved as a control group (n=20).

Table 2. Number of study participants by group and sex.

	Start Count	End Count
Control female	10	7
Control male	13	13
Intervention female	21	20
Intervention male	21	20
Comparison female	24	21
Comparison male	19	19

ECOLOGICALLY ORIENTED INQUIRY

Certainty and authenticity represent two ends of the spectrum for inquiry in the social sciences. Certainty emphasizes method with meticulous manipulation of variables often resulting in a loss of authenticity. Research design with a high degree of certainty compromises relevance with its exclusive emphasis of method over meaning and manipulation over understanding (Gibbs 1979). On the other hand, research design with a high degree of authenticity compromises rigor due to its high sensitivity to human subtlety. An extreme level of authenticity can undermine the objectivity and generalizability of the study (Gibbs 1979). This study seeks to accomplish a "genuine cross-fertilization" between certainty and authenticity; although the blending requires compromise at both poles so that neither one by itself provides a satisfactory explanation. This approach, called *ecologically oriented inquiry*, allows the researcher to examine unique and diverse human behavior in a real-world context using a theoretical-deductive conceptual framework derived from prior studies conducted in an environment of certainty and meticulous manipulation of variables. In other words, this research was designed to answer theoretical questions while using a real-world context to gather data.

The variables of interest are described below along with a discussion of limitations to the manipulation of variables and two additional pertinent considerations: justification for the content selected and for the use of technology as an instructional tool.

VARIABLES

The independent variable was the geovisualization tool utilized. The intervention group used GST: specifically a virtual globe with map layers created with ArcMap. The comparison group used non-digital paper-and-pencil maps printed from images created using the virtual globe and map layers. The dependent, or measured variables, were the pretest/posttest assessments of spatial skills and content, the attitude survey, and the instructional product (task-based). Students in both the intervention and comparison groups were familiar with the GST utilized. All the students had participated during the academic year in a partnership between the school and the university which developed and integrated instructional activities utilizing GST. All the students participating in the study had prior experience with GST in the classroom. Thus, variation due to a technology gap among the students was reduced because of the shared classroom experiences in GST.

The intervention was conducted in the classroom as part of the students' normal instruction. Ecological validity was high because the process and instruction were similar to what the students expected on a daily basis. Ecological constants included instructional content between the intervention and comparison group. Scripting between the two groups was provided to maintain consistency in the information and prompts provided. Instruction was delivered to the split classes during the same time period. And, explicit attention was given to visualization strategies in both groups.

Confounding variables are extraneous variables that could affect the behavior of the participants or have an effect on one or more of the measured variables. Subject variables such as sex, class period, age, prior experience, or motivation for the subject could have an effect on outcomes. Experiment design issues may have had an effect and included the characteristics and manner of presentation between the two instructors. Physical environment can have a confounding effect. These variables included time of the class period, interruptions to class (e.g., public announcements, individuals arriving late to class or leaving early), and attrition because of a schedule change or relocating to a different school.

Using a pretest-posttest with control group design, the effect of confounding variables can be controlled to an extent by examining the degree of equivalence among groups prior to any treatment. No guarantee exists, even with a stratified random grouping, that the groups are comparable at the baseline nor does a posttest-only design allow consideration for within group variability (Bonate 2000). Large individual differences in spatial skills among subjects within the same group have been identified in prior work (Lajoie 2003; Wolbers and Hegarty 2010) and represent a major source of variance that should be controlled for if possible. Utilizing a pretest/posttest design attempts to identify and consider this anticipated variation. Prior experience with GST was assumed because all the students had worked earlier in the academic year on other virtual globe and GIS activities as part of their participation in an NSF K-12 Education

(GK-12) project, Advancing Geospatial Skills in Science and Social Science (AGSSS). During the school year, GK-12 fellows (graduate students) and teachers collaborated to revise, develop, and implement curriculum projects which featured spatial thinking and the application of GST (http://agsss.tamu.edu/).The researcher for this study was one of the GK-12 fellows. The students in this sample, via curriculum implemented through AGSSS, participated in at least five geography lessons utilizing GST prior to the study's intervention.

Motivation is a crucial factor in academic success. Educators typically encounter two types; motivation arising from a conditioned expectation of academic success and intrinsic motivation arising from a personal interest in the subject or activity (Mills 1991). Equivalent motivation of the first type and effective study habits were assumed among the participants because all were honor students with good academic standing.

CONTENT SELECTION

The recent importance of high-stakes testing in Texas and throughout the United Sates necessitates a thoughtful and reflective consideration of the content to be used in an intervention study such as this. Central place theory was selected as the study's topic because it is a component of the required state and national standards and because the spatial patterns associated with market centers can be displayed and visualized using tools of representation such as Virtual Globes and paper maps.

According to *Geography for Life, National Geography Standards* (1994, p.34), a geographically informed person "sees meaning in the arrangement of things in space."

More specifically, standard 3 states the geographically informed person knows and understands, "how to analyze the spatial organization of people, places, and environments on Earth's surface." Standard 11 specific to "Human systems," specifies knowledge and understanding of the patterns and networks of economic interdependence. Central place theory and the patterns of settlement that emerge as a result of economic interdependence are areas of geographic content that apply spatial thinking.

Perhaps more relevant to the Texas geography teacher are the Texas Essential Knowledge and Skills (TEKS) for world geography. Item 6A states, "The student is expected to locate settlements and observe patterns in the size and distribution of cities using maps, graphics, and other information." Both the intervention and comparison groups were engaged in this process through the study of central place theory. More specifically, under "Economics" in the World Geography TEKS, items 11A-C state, "The student is expected to map the locations of different types of economic activities; identify factors affecting the location of different types of economic activities; and describe how changes in technology, transportation, and communication affect the location and patterns of economic activities." Even though central place theory is not specifically mentioned in the TEKS, central place theory encompasses virtually all of these topics.

In considering education standards for spatial thinking, *Learning to Think Spatially* (Committee on Support for Thinking Spatially 2006, 68) identifies 11 operations typically performed in the process of "doing geoscience." Of these 11, three are critical to the perception and comprehension of central place theory: describing shape of an object [or array of objects], ascribing meaning to the shape, and recognizing shape and pattern amid a noisy background. Three other operations mentioned in *Learning to Think Spatially* might enhance the understanding of and ability to explain exceptions to central place theory in novel examples: visualizing 3-dimensional form or phenomenon from a 2-dimensional representation (e.g. imagining real-world changes in elevation based on a two-dimensional image or representation); envisioning motion through 3-dimensional space; and using spatial thinking to consider time.

TECHNOLOGY JUSTIFICATION

Bednarz (2004) outlines three justifications for incorporating Geographical Information Systems (GIS) into K-12 education: 1) GIS and GIScience support the teaching and learning of geography and environmental education; 2) GIS is an essential tool in the modern day workplace; and 3) GIS is an ideal tool for the study of environment and community. Specifically Bednarz states, "For geographic educators the most important and powerful argument for incorporating GIS into the curriculum is its purported ability to enhance spatial thinking skills (Bednarz 2004, 192)." The NRC (2006) strengthens this argument by stating that GIS has the potential not only to enhance spatial thinking skills but also to support the scientific research process (e.g., inquiry), provide workforce opportunities in the information technology sector, accommodate the full range of learners (age, learning style, and ability), and fit in to a range of educational settings.

In 2006 when *Learning to Think Spatially* (Committee on Support for Thinking Spatially 2006) was published many barriers prevented implementing a desk-top version of GIS into K-12 classrooms. These barriers included time needed to learn GIS software, availability of start-up funds, software compatibility issues, time needed to design GIS lessons, and data availability. The barriers also include human issues such as lack of pre-service and in-service GIS training, lack of administrative support, lack of teaching methods that are more compatible with learning with GIS, lack of teachers' technology skills, and inadequate content background related to geography concepts and spatial skills (Johnson 1996; Audet and Paris 1997; Bednarz 2004; Committee on Support for Thinking Spatially 2006).

Progress has been made in overcoming these barriers and bringing GST, such as GIS, to a general audience and to K-12 education. One such example is the explosion and popularity of Virtual Globes. In June 2006 Google introduced Google Earth Virtual Globe (Butler 2006). The application has evolved from being simply a visualization tool to an analytical tool allowing more GIS functionality so that limited analysis and layering options are available. Current versions of Google Earth allow a "mash-up" of remotely sensed images and GIS layers. Much of the educational benefits of GIS are now freely and easily accessible through virtual globes, such as Google Earth, and web-based GIS. Increased accessibility has helped to overcome many of the hurdles to GIS implementation in K-12 education (Metoyer 2006). For these reasons, Google Earth with GIS layers was used as the GST in this study.

TEACHING CENTRAL PLACE THEORY WITH GST – THE INSTRUCTIONAL UNIT

A two-day instructional unit was developed by the researcher and used as the intervention in the study. The instructional unit was delivered to high school honors geography students during the regular course of their school day. Each class period was 55 minutes long. This time frame did not include time for pre and posttests.

The primary purpose of the instructional unit was to instruct students on the geographic concept of central place theory using different tools of representation: GST versus paper-and-pencil maps. The activities encouraged not just acquisition of content knowledge, but the application of the knowledge to tackle new problems as is encouraged by the Geography Education Research Committee of the Road Map for 21st Century Geography Education Project (2013) and by the Next Generation Science Standards (NGSS 2013). In addition, collaborative instructional strategies, which are known to support positive learning outcomes, were used with both groups (Bransford et al. 2006; Carmichael 2009). The sequence of activities for the instructional unit was developed with this pedagogical theoretical basis. The unit was planned so that activities would build from a foundational knowledge of central place theory to an application of that theory tested on a specific case. Details of the instructional unit, by day, are described in the following sections.

Day 1 of the Instructional Unit

On the first day, both the intervention and comparison groups met together for an introduction to central place theory. The introduction utilized a guided-inquiry format and provided some background about central place theory. The students explored assumptions of central place theory using comparative examples and considered conditions that could cause variations to the assumptions of the theory.[2] Students were provided with a progression of simple to more complex examples of the spatial patterns of market centers (cities) based on central place theory. Students were directed to use their imagination to visualize the patterns they were trying to identify from the examples. Students used tracing paper to sketch straight lines among market centers of different sizes in order to help them recognize the spatial pattern of triangles and simple hexagons predicted in Walter Christaller's central place theory (Christaller 1966).

The instructor suggested visualization strategies such as imagining different perspectives when viewing a map or predicting spatial patterns among features displayed on the map. Spatial thinking was intentionally fostered by modeling and encouraging the use of spatial vocabulary, drawing students' attention to the location of objects on the maps and their inter-related shapes, and by utilizing gestures and sketches to help students visualize spatial arrangements (Newcombe 2010). A script listing specific steps of instruction and examples was followed so that each of the four classes heard the same

[2] Background information about central place theory, covered in the first day of the instructional unit, is provided in Appendix N.

explanations for central place theory, the same examples, the same questions, and the same prompts for visualization strategies.

At the end of the first day, students were assigned to one of two groups: intervention or comparison. The following day's task was described; looking for evidence on maps of the Czech Republic to support or to refute the pattern of market centers predicted by central place theory.

Day 2 of the Instructional Unit

The following day, day 2 of the instructional unit, students were divided using a stratified random sampling method. Half of the students (exclusive of the control group) received instruction in the computer lab using GST as a geovisualization tool. The other half remained in the classroom using paper maps and data tables. Working in pairs, both groups followed a written guided activity to support the investigation of the spatial patterns of market centers in the Czech Republic.

The first activity on day 2, for both groups, explored the spatial distribution of cities. The intervention group used GIS layers developed in ArcMap, converted to zipped Keyhole Markup Language files (KMZ) and displayed in Google Earth using proportional symbols to represent population size. Using the measurement tool in Google Earth, students calculated distances between various market centers. Using the road layer in Google Earth, they explored transportation routes among the market centers. Using the draw tool and without prompting, many students added bold lines directly connecting the market centers thus enhancing their ability to visualize the geometric patterns. And, by tilting the view, students in the GST intervention group were able to consider the influence of terrain on the spatial pattern of cities.

The comparison group completed the same activity. Instead of digital maps, however, they used laminated paper maps and rulers to measure distances (requiring scale conversion). The paper maps displayed the same remote-sensed images and information layers as the Google Earth representations, but lacked the dynamic interactive nature of Google Earth. Students using the non-digital maps could not change scale, orientation, or view angle. Likewise, they were not able to turn layers on and off. Instead, they viewed the layers as multiple static paper maps. Table 3 compares differences in features of the tool of representation used by the GST digital intervention group and the non-digital comparison group.

Table 3. Differences in the tools of representation.

Digital Group (Google Earth and GIS)	**Non-digital Group** (Paper maps and data tables)
Interactive: Students could adjust scale, altitude, perspective, and/or layers	**Non Interactive**: Students could not adjust scale, altitude, perspective, or layers
Adjustable Scale: Students could easily zoom in and out	**Fixed Scale**
Layering: Students could turn on and view several layers displayed on one image	**No Layering**: Students viewed layers separately on different maps
Dynamic: Images changed	**Static**: Images did not change
Non-sequential: Students could explore outside the region of interest and among the layers	**Sequential and Linear**: Students viewed separate maps in a prescribed order
Digital Measurement: Students used automated tools to measure distance and to determine scale	**Hand Measurement**: Students used a scale bar and a ruler to estimate distance and scale

The second activity on day 2 was to examine where lower-order goods versus higher-order goods were available, and how the location of these goods was associated with the spatial distribution of market centers. Students explored the spatial pattern of McDonalds as an example of a lower-order good among market centers in the Czech Republic. Students then used the same steps to examine spatial patterns of higher-order goods, Audi car dealerships. The intervention group viewed McDonalds and Audi dealership locations as layers created using ArcMap in Google Earth. The non-digital comparison group was provided a table with the number of McDonalds and Audi dealerships per market center identified by city name. Population count by city was included in the table. Cities were marked with proportional symbols representing population size on a laminated map. Students in the comparison group considered the spatial patterns in the number of lower-order and higher-order goods using the table listings and laminated paper maps.

Students in both groups were given questions on a printed handout. The questions guided them through the process of evaluating spatial patterns among market centers displayed on the map and the expectations and assumptions anticipated based on central place theory. An example question was, “Does the ratio (relative numbers) of big cities to small cities match what is expected based on central place theory?” The set of questions were the same between the two groups (appendix B). In the case of the intervention group, information about population distribution was in a dynamic spatial display. The comparison (non-digital) group viewed the same information in a non-spatial format with tables indicating city name, population, and number of McDonald restaurants or number of Audi dealerships. The written instructions were slightly different for the groups in order to be appropriate for the type of representation used. A script for instruction to the two groups was used to maintain similar format and delivery among the four divided classes. Figure 4 illustrates the sequence of activities in the study design.

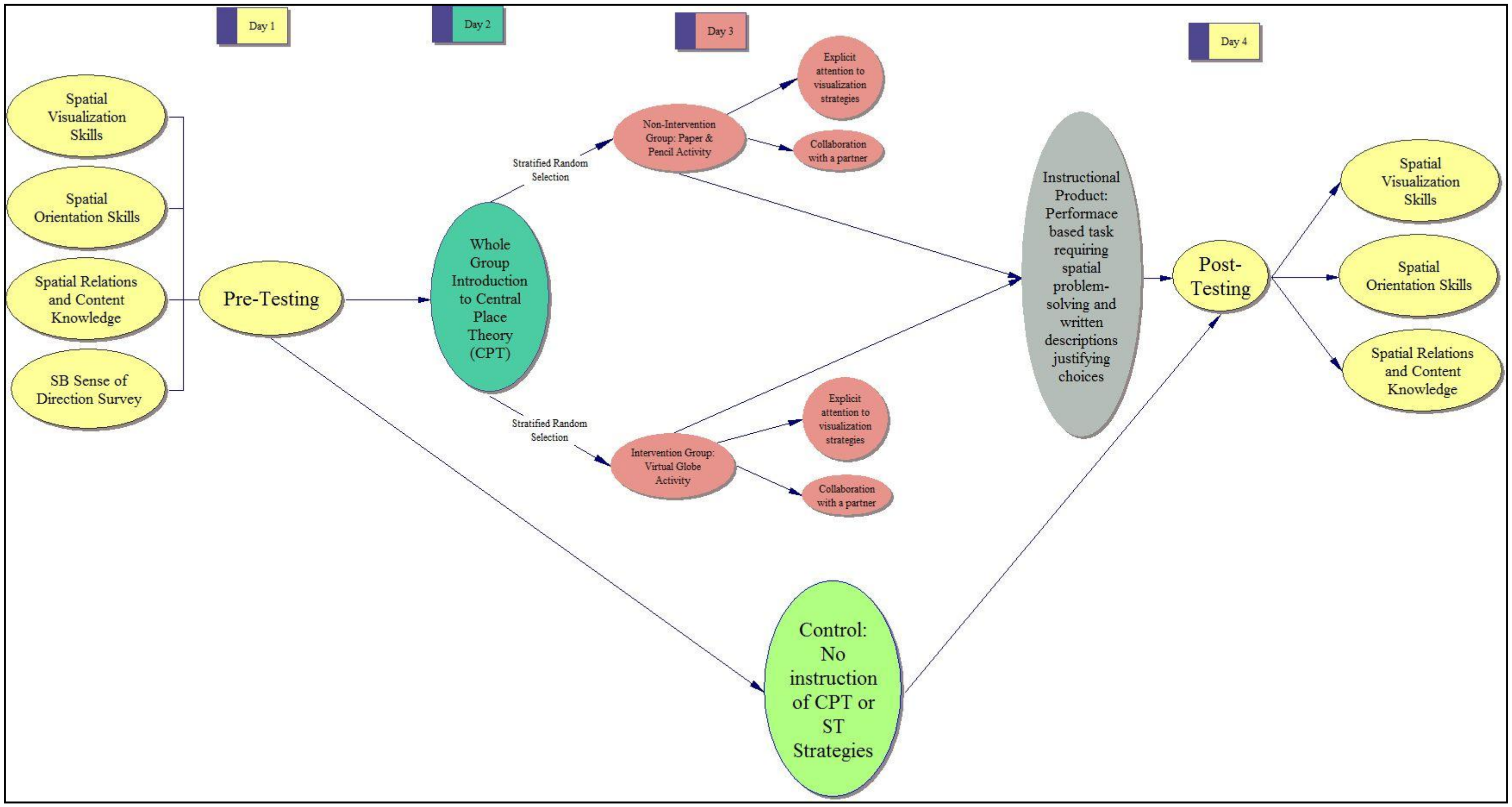


Figure 4. Sequence of activities in the study design.

INSTRUMENTATION

One week prior to the two-day instructional activity, pre-assessments were obtained from participating students for spatial visualization skills, spatial orientation skills, spatial relations content knowledge, and self-reported sense of direction. A practice item was given prior to the timed portion of each spatial skill test (visualization and orientation) so that there was no delay caused in the timed portion by reading of instructions, confusion over the instructions, or a lack of understanding of the task. Nineteen days following the instructional activity, posttests were obtained for spatial visualization skills, spatial orientation skills, and spatial relations content knowledge (Table 4).

The instruments for spatial visualization skills and spatial orientation skills were piloted in South Korea in the summer of 2008 during which several problems with the instrument were found. First, the two-dimensional section of the instrument was too short. The majority of the participants completed all items easily within the two-minute time frame. Second, the pretest and posttest did not differ sufficiently and lacked an adequate time period between the pretest and the posttest (in one case the time lapse was one day, the second case it was three hours). As a result, it was impossible to control for a test-retest effect, and it was difficult to measure gains because most of the participants scored near 100 percent on the pretest. The two-dimensional visualization instrument was revised by adding to the total number of items in the pretest and by creating a posttest with several novel items interspersed randomly among items repeated from the pretest. The three-dimensional section was of adequate length as the South Korean students were not able to complete the 14 items within the two-minute time frame. However, the elapsed time between the pretest and posttest was not sufficient to control for a testing effect and a lack of a control group did not allow for the isolation of a testing effect (Ary et al. 2010).

For this study, the posttest was administered 25 days after the pretest in order to diminish a test-retest effect. A control group was used for comparison to determine the extent practice provided by the testing affected the participants' spatial skills.

Table 4. List of instruments.

Instrument Name	Placement	Source	Type of Data
Santa Barbara Sense of Direction Survey (SBSOD)	Pre-only	Hegarty et al (2002)	Survey data Not timed Likert 6-point scale
Spatial Visualization Skills: Mental Rotation	Pre & Post	Adapted from Ekstrom (1976)	Quantitative Timed (2 min.) Same/Different
Spatial Orientation Skills: Object Perspective Test	Pre & Post	Adapted from Hegarty & Waller (2004)	Quantitative Timed (2 min.) Angular measure
Spatial Relations Content Test	Pre & Post	Developed for this study	Quantitative Not timed Multiple choice

Santa Barbara Sense of Direction Survey

Instrument Description

Sense of direction is a proxy for spatial orientation. The SBSOD survey was developed as a predictor of spatial orientation skills. A series of four separate validity studies (Hegarty et al. 2002) suggest that the SBSOD survey is related to authentic tasks that require re-orientation of self in a real-world large scale setting. Scores, from prior studies, have been correlated with field tests that involve orientation within the environment. The SBSOD survey was selected for this study to establish a baseline of students' self-perceptions regarding their sense of direction and navigation skills and to serve as a tool to further analyze results of the orientation skills test and the spatial relations test.

The SBSOD survey is a collection of questions that ask individuals to self-report their navigational abilities, preferences, and experiences. The survey is composed of 17 items on a six-point Likert scale ranging from strongly agree to strongly disagree (Likert 1932). Questions reflect self-efficacy for tasks such as giving directions, judging distances, and reading maps. Among the 17 items, 8 were negative statements that reflect a lack of confidence or self-efficacy related to navigation and sense of direction (items #2, 6, 8, 10, 11, 12, 13, and 15) and 9 items were positively stated questions (items #1, 3, 4, 5, 7, 9, 14, 16, and 17). Item examples are provided in Figure 5.

9. I am very good at reading maps.

strongly agree 1 2 3 4 5 6 strongly disagree

10. I do **not** remember routes very well while riding as a passenger in a car.

strongly agree 1 2 3 4 5 6 strongly disagree

Figure 5. SBSOD survey item examples

Test Setting and Administration

The SBSOD survey was administered in the classroom as a pre-assessment only on the same day as the other pre-assessments. The survey was not timed. Participants were provided unrestricted time for completion of the survey. The survey was administered on a hand-out as a paper-and-pencil test. Participants were provided with the following written instructions:

> This survey consists of several statements about your spatial and navigational abilities, preferences, and experiences. After each statement, you should circle a number to indicate your level of agreement with the statement. Circle “1” if you strongly agree that the statement applies to you, “6” if you strongly disagree, or some number in between if your agreement is intermediate.

Data Scoring and Analysis

Performance on the survey was measured as a sum score of the seventeen items. One point was allotted for a response of “strongly agree” through six points for “strongly disagree” on negatively stated items. For positively stated items, the scale was reversed, one point was allotted for a response of “strongly disagree” through six points for a response of “strongly agree.” In this manner of coding, when points from all 17 items were summed, the aggregated score provided a proxy for self-efficacy for navigation and sense of direction. The scores from the pre-assessment were analyzed using an exploratory factor analysis to explore latent constructs that may help explain differences in outcomes among groups and/or individuals. Descriptive statistics were used to provide an overview of the responses by group. The frequency and distribution of scores from the SBSOD were also used to establish three categories of participants: low self-efficacy for spatial thinking, average self-efficacy for spatial thinking, and high self-efficacy for spatial thinking. Categories of self-efficacy for spatial thinking were then used in an analysis of variance (ANOVA) examining how the low, average, and high categories performed pre to post intervention in spatial skills (visualization and orientation) and in spatial relations content knowledge.

Spatial Visualization Skills

Instrument Description

Mental rotation from an allocentric viewpoint is an example of spatial visualization (Golledge and Stimson 1997; Hegarty and Waller 2004; Zacks and Tversky

2005). It requires the mental manipulation of an object or array of objects with no imagined change to the individual's viewpoint or orientation. Mental rotation of both two-dimensional and three-dimensional objects is a standard test for spatial visualization that has been used in many studies measuring spatial skills (Quaiser-Pohl 2003; Burton 2003; Voyer, Voyer, and Bryden 1995).

Two-dimensional items selected for this study, simple geometric shapes, were modified from Ekstrom et al. (1976). The exercise required the participants to compare one example item to four other items that were the same shape and size but have been rotated (transformed on one axis) or have been rotated and flipped (transformed on two axes). The task required the students to distinguish similar from different shapes. If the object was rotated along one axis but not flipped, it would be marked "S" for same. If the object was flipped creating a mirror image of the example item, it would be marked "D" for different (Figure 6). Twenty-four items of this type were in the pre and posttests for two-dimensional visualization.

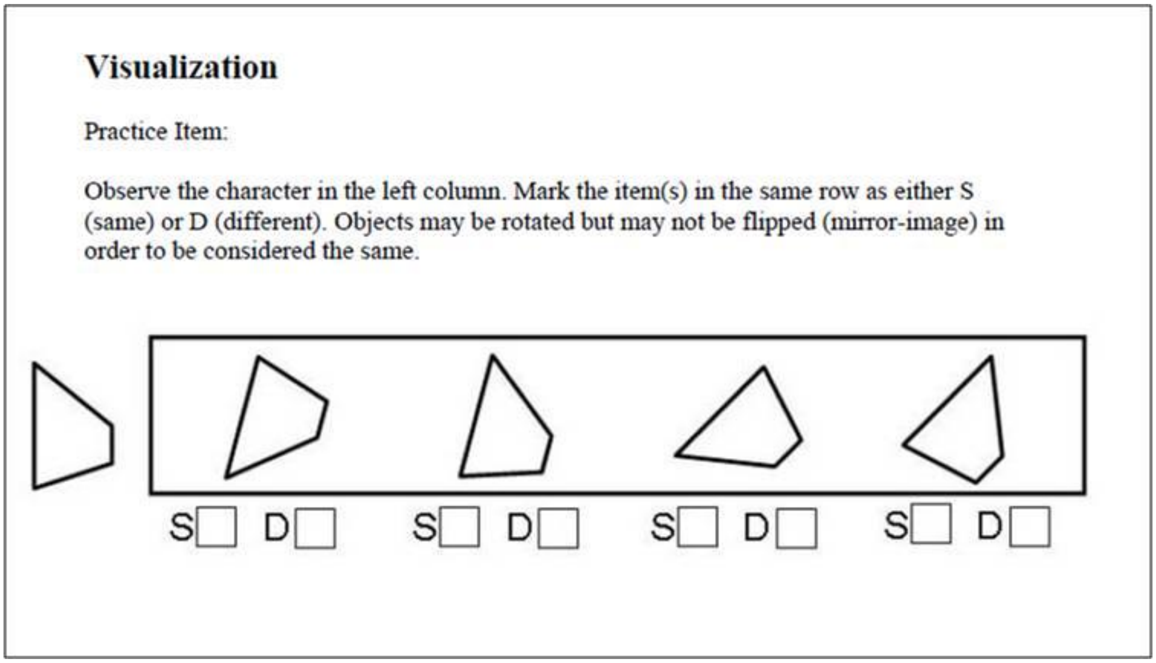


Figure 6. 2-D visualization test item example.

Three-dimensional test items selected to assess spatial visualization skills, cubes marked with patterns of either round dots in a fashion similar to dice or with six unique geometric shapes, were modified from Ekstrom et al. (1976). The participant was required to compare one example cube to three other cubes in the same row that are the exact same shape and size but have been rotated sequentially one face at a time. The task was to number the three comparison items in the correct order that the cube was rotated. Three of six faces were visible on each cube. The cube could turn or rotate only one face at a time, but it could be rotated in any direction or along any axis (Figure 7). The test was comprised of 14 items of this type in both the pretest and posttest for three-dimensional visualization; eight items used dots on the cube faces and six items used unique geometric shapes.

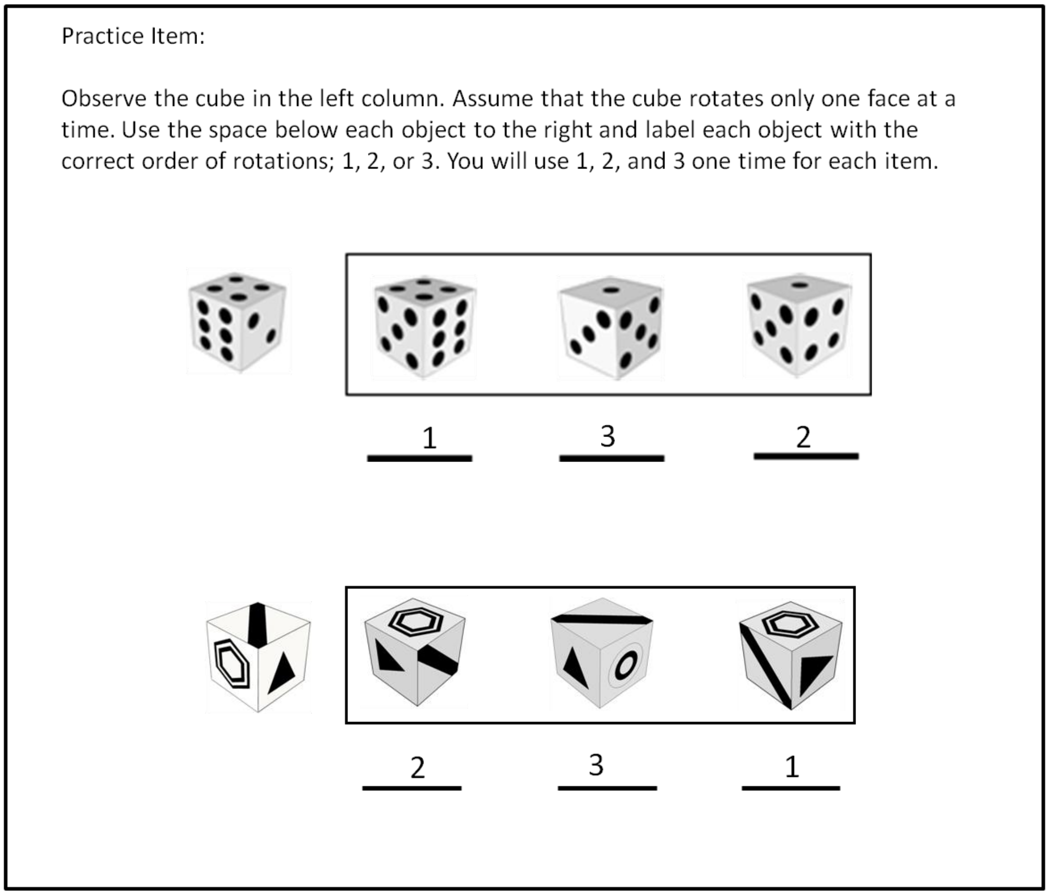


Figure 7. 3-D visualization test item examples.

Setting and Administration

Participants were given two minutes to complete the 2-D spatial visualization test and two minutes to complete the 3-D spatial visualization test. Before each test, the researcher reviewed one item as an example to ensure the participants knew what was expected and to answer any questions about the test prior to the start of the test. Participants did not have to read or interpret instructions during the two minutes of the test. Participants were instructed to complete as many items as possible with the greatest degree of accuracy within the two-minute time limit.

The 2-D and 3-D spatial visualization tests were given as a pretest and as a posttest. The pre and posttests were the same with regard to number and types of items. The posttest differed from the pre by sequence of items and sequence of answer choices within each item.

Data Scoring and Analysis

Performance on the spatial visualization skills tests was measured with two scales: accuracy and efficiency. Accuracy was determined by dividing the number of correct items by the number of items attempted, then multiplying by 100 to obtain a percentage score. Efficiency was determined by dividing the number of items attempted by the total number of items on the test, then multiplying by 100 to obtain a percentage score. Accuracy and efficiency scores were compared using Pearson's correlation test to determine statistical independence. The two scales were not significantly correlated (R = 0.02 for 2-D, R = 0.03 for 3-D) and were, subsequently, assumed to be independent variables. For *independent* variables, a combined average is calculated by taking the product of the averages. A combined score of the two independent variables was calculated by multiplying the average accuracy score and the average efficiency score, then dividing the product by 100 to obtain a combined percentage score. Descriptive statistics were obtained for comparison among groups for accuracy, efficiency, and combined scores. Mean scores on the pre and posttests were analyzed using a paired sample t-test. An alpha level of 0.05 was used to determine significance between pre and posttest scores. Accuracy scores were used in conjunction with categorical data for an analysis of variance to explore differences among and within groups.

Spatial Orientation Skills

Instrument Description

Assessing spatial orientation skill using paper-and-pencil items is difficult because the representation of a large three dimensional area is being illustrated in a small two-dimensional space. Spatial orientation is often measured using an authentic performance such as pointing or walking to indicate a bearing or direction. Hegarty and Waller (2004) developed a paper-and-pencil test, The Object Perspective Test, intended to assess orientation skills as an egocentric transformation skill measuring an individual's re-orientation ability. Alpha Cronbach internal reliability for the Object Perspectives Test administered in two sets of experiments ranged between 0.79 and 0.84. Analysis demonstrates this task as independent from mental rotation tasks indicating a separate and measurable spatial skill (Hegarty and Waller 2004). A modified version of the Object Perspective Test was piloted in South Korea in the summer of 2008. The test performed well. Students could understand and perform the task. The researcher used results of the task to measure accuracy and student performance. The Object Perspective Test was utilized in this study to measure orientation skills of the students and to explore the relationship among spatial skills, self-efficacy for sense of direction and navigation skills, and changes to students' content knowledge of a spatial concept.

The spatial orientation test had 20 items in both the pretest and posttest. Items for the pretest and posttest were the same items, but they were presented in a different order in the posttest than in the pretest. Participants were required to imagine standing at one feature on the "map" and imagine facing a second feature. They then pointed to a third feature by drawing a line to indicate the angle of difference between the feature they were facing and the feature they were pointing to (Figure 8).

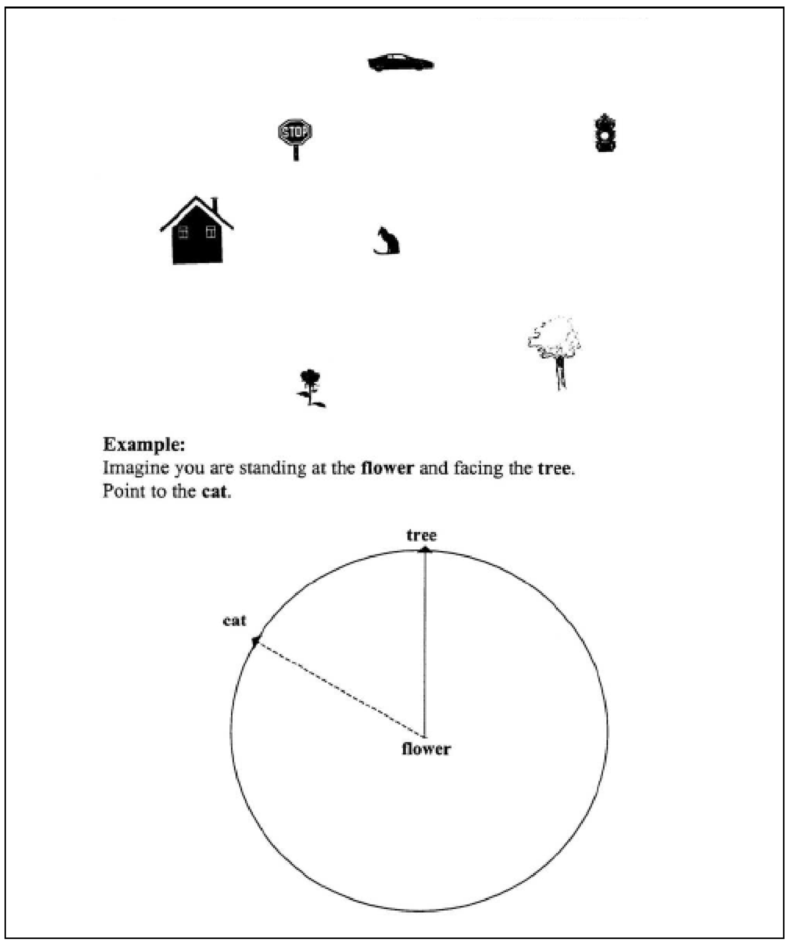
For the questions on each page, you should imagine that you are standing at one object in the array (named at the center of the circle) and facing another object (named on the edge of the circle). Your task is to draw an arrow to indicate the direction you would point from your imagined position and orientation to the third object

There are **20 items** in this test, **two on each page**. For each item, the array of objects is shown at the top of the page and the answer circles are shown at the bottom.

Please **do not pick up or turn the test booklet**, and **do not make any marks on the maps**.

Look at the example below. Your task is to draw a second arrow in the circle to indicate the direction you would have to point in order to **point to the cat**.

This section is **time-limited to 2 minutes**.



Adapted from Hegarty & Waller (2004) Perspective Taking/Spatial Orientation Test

Figure 8. Spatial orientation test item example

Setting and Administration

Participants were given two minutes to complete the spatial orientation test. Before the test, the researcher went over one item as an example to ensure the participants knew what was expected and to answer any questions about the test prior to the timed portion of the test. Participants did not have to read or interpret instructions during the two minutes of the test. Participants were instructed to complete as many items as possible with the greatest degree of accuracy within the two-minute time limit.

The spatial orientation tests were given as a pretest and as a posttest. The pre and posttests had the same number and type of items. The posttest differed from the pre by the sequence of items and the posttest had several new, equivalent items that replaced items on the pretest.

Data Scoring and Analysis

Similar to the spatial visualization tests, performance on the spatial orientation tests was measured on two scales: accuracy and efficiency. Accuracy was calculated by first determining the degrees of difference (out of 360) between the correct measured angle and the angle drawn by the participant. For example, if the actual measured angle, determined by laying a protractor directly on the printed example, was 30 degrees; and the student drawn angle, determined by laying the protractor on the participant's drawn lines, was 25 degrees; degrees of difference was five. In order to convert degrees of difference to a percent of accuracy and to normalize the average accuracy among participants that answered varying number of items; the following steps were used:

1. Subtract the degrees drawn from the actual correct degrees
2. Repeat step 1 for each item attempted
3. Square each of the differences
4. Sum the squares
5. Take the square root of the sum of the squares
6. Divide the value from step 5 by the number of items attempted to obtain the average degree of difference
7. To obtain a percent value for accuracy (rather than difference), subtract the average degree of difference from 180 degrees then divide by 180 degrees

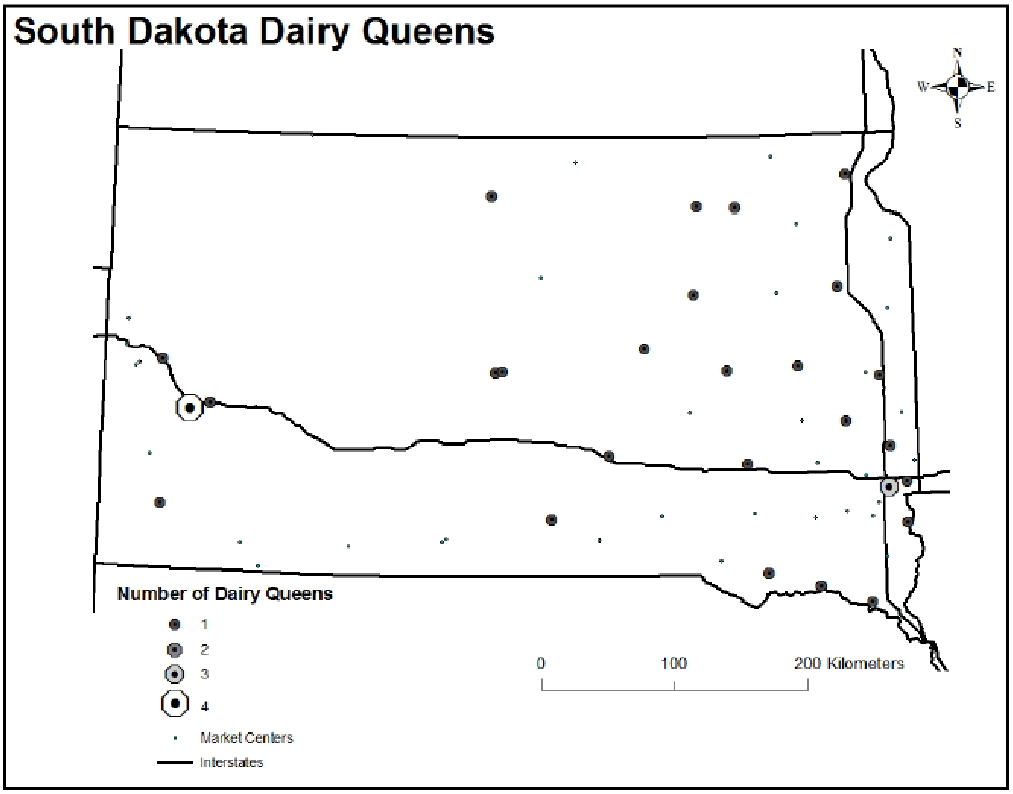
Efficiency was determined by dividing the number of items attempted by the total number of items on the test, then multiplying by 100 to obtain a percentage score. Accuracy and efficiency scores were compared using Pearson's correlation test to determine statistical independence. The two scales were significantly correlated (R = 0.37, $p<0.01$). Therefore, they were not assumed to be independent variables and a combined score was not calculated. Descriptive statistics were obtained for comparison among groups for accuracy and efficiency. Mean scores on the pre and posttests were analyzed using a paired sample t-test. An alpha level of 0.05 was used to determine significance between pre and posttest scores. The combined scores were used in conjunction with categorical data for an analysis of variance to explore differences among and within groups.

Spatial Relations Content Test

Instrument Description

Spatial relations include a broad and diverse set of higher-level, spatial thinking skills. The test items developed for the spatial relations content test were based on 1) spatial operations described in *Learning to think spatially: GIS as a support system in the K-12 curriculum* (Committee on Support for Thinking Spatially 2006, 68); 2) examples of spatial relation abilities listed by Golledge and Stimson (1997, 158); 3) level of spatial thinking assigned using a taxonomy of spatial thinking (Jo and Bednarz 2009); and 4) content relevant to central place theory. The test was created to measure changes in students' understanding of central place theory from a spatial-relations-skill perspective. In other words, to answer questions correctly, required spatial skill and content knowledge. Drawing on examples from Lee's (2005) spatial relations instrument and Jo and Bednarz's (2009) taxonomy for evaluating questions for spatial thinking, questions were developed that integrated concepts of space, tools of representation, and higher level processes of reasoning to assess students' understanding of central place theory.

Questions were categorized as 1) requiring primarily spatial skills to answer, 2) requiring primarily content knowledge specific to central place theory, or 3) task based questions. The first category is referred to in data analysis as *content-independent*, the second as *content-dependent,* and the last as *task-based*. All three question categories measure spatial thinking as all include the essential components of spatial thinking as defined in *Learning to Think Spatially* (Committee on Support for Thinking Spatially 2006); concepts of space, tools of representation, and higher level processes of reasoning. The content-dependent category, however, is unlikely to be answered correctly without some understanding of the generalizations and assumptions of central place theory. Figure 9 provides an example of a content-independent and a content-dependent question.



Example of a content-independent spatial relations question:

A general spatial pattern displayed by the location of Dairy Queen restaurants is:

A. Evenly spaced and distributed except in the northwest
B. Random: there is no pattern to the restaurants' locations except in the northwest
C. Clustered: The restaurants are grouped close together except in the northwest
D. Linear: Most of the restaurants are located close together along the interstates except in the northwest

Example of a content-dependent spatial relations question:

Based on generalizations of spatial patterns predicted by central-place theory which of the following would **NOT** be an explanation for the lack of Dairy Queens in the NW?

A. Transportation costs are much higher based on time of travel in this region
B. People in the NW region do not prefer coffee or ice cream
C. There is too little population to provide the threshold needed for this order of goods
D. The topography in this region is flat and homogeneous

Figure 9. Spatial relations content test item example

The taxonomy of spatial thinking (Figure 10) developed by Jo and Bednarz (2009) incorporates the three components of spatial thinking defined in *Learning to Think Spatially* (Committee on Support for Thinking Spatially 2006). This includes 1) concepts of space, 2) using tools of representation, and 3) processes of reasoning. Questions created for this study were matched by taxonomy scale between the pretest and posttest items. Pretest items were similar to paired posttest items with regard to spatial concept utilized, cognitive process required, and type of representation used.

The objective of this assessment was to measure changes in students' understanding of the spatial concept of central place theory after an instructional intervention. Questions were intentionally clustered in the top range of the taxonomy in an effort to avoid perfect scores by students on the instrument. Questions in the top three cells of the taxonomy (cells 22, 23, or 24) reflect complex spatial concepts and use of a spatial representation. The cognitive process required for the item could be input, processing, or output with the question still placed in one of the top three cells. The intent was not to assess basic competency or understanding but to measure gains due to a specific instructional strategy. If a student scored 100 percent on the pretest, the only measurable change that could occur would be a negative one.

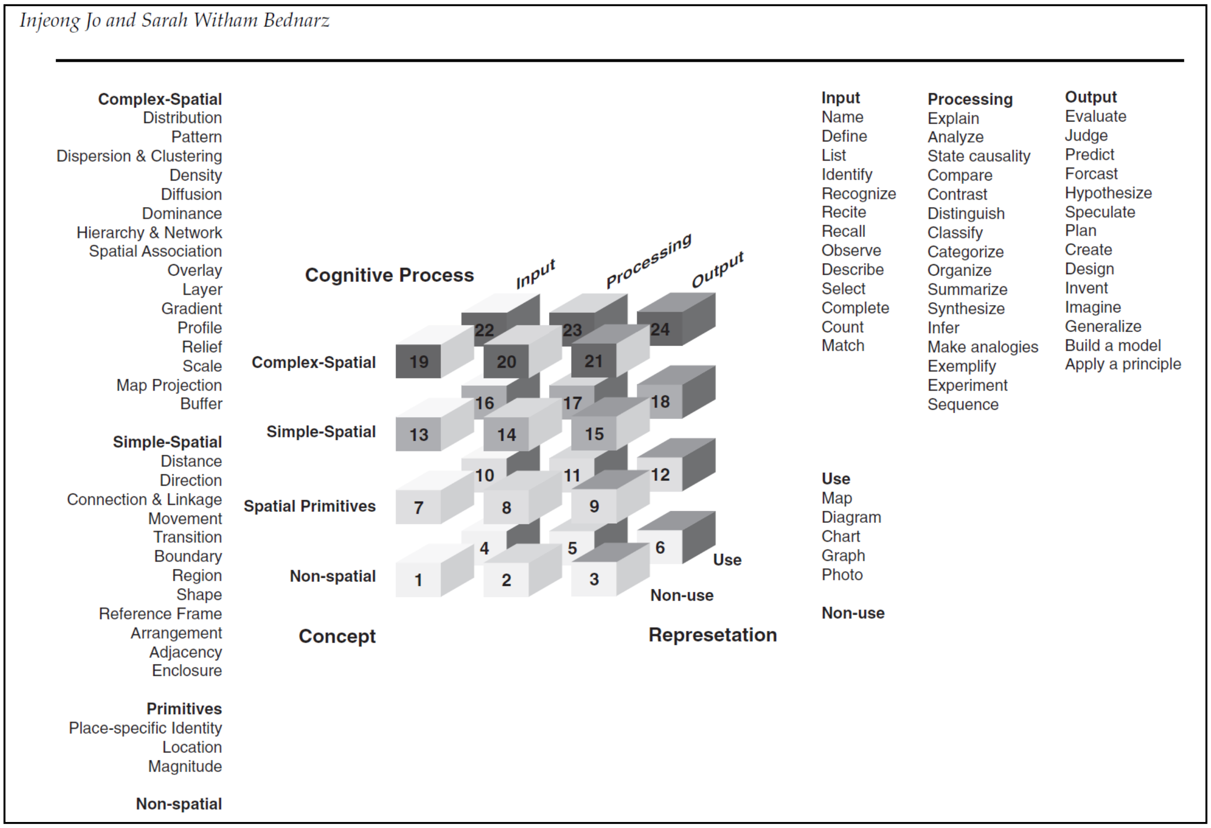


Figure 10. Taxonomy of spatial thinking (Jo and Bednarz 2009).

The challenge in designing the questions was to match pretest questions and posttest questions with respect to content and level of difficulty without simply repeating the same questions. Using the taxonomy of spatial thinking, pretest questions closely matched posttest questions. Table 5 provides an example of how one question in the spatial relations content was classified.

Table 5. Example classification of a spatial relations content test item

Content-independent example (Item from figure 3.7)

Question: A general spatial pattern displayed by the location of Dairy Queen restaurants is:		
Content Standard (TEKS)	Spatial Operation (NRC 2006)	Spatial Relation Ability (Golledge and Stimson 1997)
11B: Identify factors affecting the location of different types of economic activity	Recognizing shape and pattern amid a noisy background	Associating and correlating spatially distributed phenomena

Taxonomy of Spatial Thinking (Jo and Bednarz 2009)			
Concept of Space	Cognitive Process	Tool of Representation	Taxonomy Scale
Complex-spatial: Pattern Distribution	Input: Identify Select	Use: Map	22

In addition to the content-dependent and content-independent multiple choice items, the spatial relations content test had two task-based items. The intent behind the task-based questions was to assess the participants' skills in evaluating spatial information in order to make a decision or to solve a problem. Figure 11 provides an example of a task-based item.

Task:

Imagine you are the regional manager for Dairy Queen in South Dakota. Because of the weak economy, you must close one of the Dairy Queen stores.

The store you close must be in a town with only one exiting Dairy Queen. Other criteria are 1) a distance at least 50 km off the interstate but no more than 100 km, 2) the smaller the population of the town the better, and 3) a location where the least amount of travelers are likely to pass through.

Circle the Dairy Queen on the map to indicate the best location.

Figure 11. Example of a task-based item in the spatial relations content test

Setting and Administration

The spatial relations content test was administered in the classroom as a pretest and as a posttest on the same day as the other tests. The spatial relations test was not timed. Participants were provided unrestricted time for completion of this test. The test was administered on a hand-out as a paper-and-pencil test.

Data Scoring and Analysis

Performance on the test, other than the task-based items, was measured by total number of questions answered correctly. Items correct were grouped for an overall percent score, content-dependent percent score, and content-independent percent score. Descriptive statistics were obtained for comparison among groups for accuracy, efficiency, and combined scores. Mean scores on the pre and posttests were analyzed using a paired sample t-test. An alpha level of 0.05 was used to determine significance between pre and posttest scores. The combined scores were used in conjunction with categorical data for an analysis of variance to explore differences among and within groups.

Task-based items were assessed on a tiered basis with one best choice (top tier, three points), followed by several good choices (second tier, two points), then choices that met at least one criterion (third tier and one point), and choices that did not meet any of the criteria (zero points). The posttest task-based items were more difficult for the participants than the pretest task-based items making it unsuitable to address the research questions. Consequently, the task-based items were not included in the final analysis.

SUMMARY

The relationships explored here have not been previously examined. Although predicted outcomes have been stated based on prior research, this study seeks to explore some of the associations presented in current literature arguing for the integration of geospatial technologies into K-12 education for the purpose of facilitating spatial skills (NCGE 1995; Kerski 2003; Bednarz 2004; Committee on Support for Thinking Spatially 2006). This is an empirical quasi-experimental study exploring relationships among spatial skills, spatial concept learning, and appropriate instructional design integrating geospatial technology to teach spatial concepts. The expected outcome or purpose of this project is a better understanding of what works and what does not work, and for whom, in the context of instructing spatial skills and concepts using geospatial technology.

Two different instructional tools were utilized by the researcher to teach a spatially dependent geographic concept for the purpose of examining the influence of GST on spatial skills and content knowledge. The intervention group utilized digital geospatial technologies. The comparison group utilized static paper-and-pencil maps. Data on sex, handedness, spatial skills, self-reported sense of direction, and content knowledge were collected. Results of the data analyses are discussed in Chapter IV.

CHAPTER IV

ANALYSIS AND RESULTS

Analysis of the data is discussed in this chapter. Discussion is organized by the three research questions. Descriptive statistics are presented first, followed by inferential statistics used to examine each of the three research questions.

Research Questions:

1) What is the effect of using GST as an instructional tool on students' spatial thinking skills?

2) What is the effect of using GST as an instructional tool on students' content knowledge of a spatial concept in geography?

3) What is the relationship among spatial thinking skills, self-attitudes towards spatial and navigational abilities, and change in students' content knowledge of a spatial concept in geography?

QUESTION 1: EFFECT OF GST ON SPATIAL THINKING SKILLS

Three participant groups (control, comparison, and intervention) completed a set of tests intended to measure spatial skills. The spatial skills assessed were 2-D spatial visualization, 3-D spatial visualization, and spatial orientation. The tests were administered using a repeated measure design; one set was administered prior to intervention and the second set was administered following the intervention. Efficiency and accuracy scores were calculated for each test. The purposes of the spatial skills test were to (1) determine starting levels of spatial skill in the participants, (2) quantify change to participants' spatial skills following the intervention, and (3) explore differences in the three groups regarding change to spatial thinking skills following the intervention.

Accuracy for 2-D spatial visualization increased significantly pre to posttest (5.9 percent gain, p=0.00), with no change in the rate of efficiency. Accuracy for 3-D spatial visualization accuracy also increased significantly pre to posttest (8.0 percent gain, p=0.00), with a significant increase in the rate of completion, or efficiency, (8.8 percent, p=0.00). Accuracy scores for spatial orientation decreased slightly, with a large significant gain for efficiency (10.7 percent, p=0.00). Maximum scores for all three spatial skills tested were relatively high in the pretest, and either at or near 100 percent in the posttests. In addition, measures of variance (standard deviation scores) were large, especially for 3-D spatial visualization accuracy. Results for all three groups (control, comparison, and intervention) are combined in Table 6 which displays a summary of the descriptive statistics for the 3 spatial skills tests.

Table 6. Descriptive statistics for the spatial skills tests with all groups combined.

	n	Minimum	Maximum	Mean	Std. Deviation
Pre 2-D Efficiency (%)	109	12.50	85.42	31.52	10.39
Post 2-D Efficiency (%)	101	15.63	62.50	32.27	10.55
Pre 2-D Accuracy (%)	109	41.67	100.00	82.38	14.47
Post 2-D Accuracy (%) ł	101	47.22	100.00	88.28	12.07
Pre 3-D Efficiency (%)	109	14.29	78.57	37.13	12.31
Post 3-D Efficiency (%) ł	101	7.14	92.86	45.90	17.88
Pre 3-D Accuracy (%)	109	16.67	100.00	69.45	22.81
Post 3-D Accuracy (%) ł	101	22.22	100.00	77.45	20.06
Pre Orientation Accuracy (%)	109	39.02	98.73	84.91	11.71
Post Orientation Accuracy (%)	101	50.00	98.57	82.74	11.38
Pre Orientation Efficiency (%)	109	15.38	76.92	44.67	12.32
Post Orientation Efficiency (%) ł	101	23.08	100.00	55.37	16.43

ł Statistically significant difference at the 0.05 level between the pretest and the posttest mean scores.

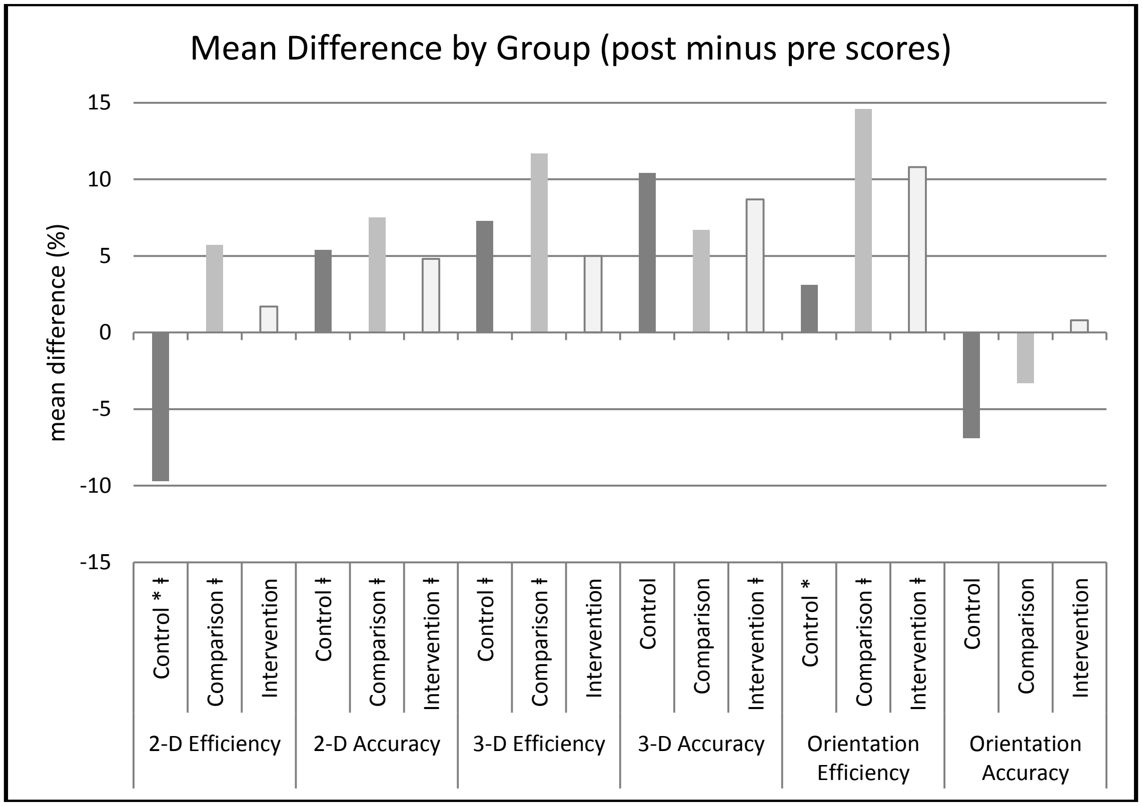
Even though the posttests had different items than the pretests, the format and style were the same. It is possible, then, that any gains in efficiency (number of items completed) or gains in accuracy (degree of correctness in items completed) could have been due to a test-retest effect rather than as a result of the intervention. Pretest scores were subtracted from posttest scores in order to obtain a score of difference for comparison for the three groups. The mean scores, pre and post, were compared using a paired sample *T* test. Significant differences existed for the comparison and intervention groups compared to the control group for efficiency in 2-D spatial visualization and spatial orientation. No significant difference in accuracy existed in the groups for any of the three spatial skills measured. In fact, the control group and the comparison group showed an insignificant loss in accuracy from pre to post for spatial orientation skills. Table 7 summarizes the mean scores of difference by spatial skill test and by group.

Table 7. Mean scores of difference compared by spatial skill test and by group.

		n	**Pre Mean (std)**	**Post Mean (std)**	**Mean Difference (std)**	**Sig.**
2-D Efficiency	Control * ł	20	37.9 (13.1)	28.3 (12.2)	-9.7 (9.8)	**0.00**
	Comparison ł	40	28.4 (8.1)	34.0 (9.8)	5.7 (9.1)	**0.00**
	Intervention	40	30.8 (9.3)	32.3 (10.2)	1.7 (12.5)	0.40
2-D Accuracy	Control ł	20	88.0 (8.5)	93.8 (5.8)	5.4 (8.1)	**0.01**
	Comparison ł	40	78.6 (16.7)	86.6 (12.6)	7.5 (12.2)	**0.00**
	Intervention ł	40	82.6 (13.8)	86.9 (13.2)	4.8 (12.7)	**0.02**
3-D Efficiency	Control ł	20	33.9 (10.8)	42.1 (14.8)	7.3 (13.9)	**0.03**
	Comparison ł	40	38.1 (12.6)	49.8 (18.1)	11.7 (15.5)	**0.00**
	Intervention	40	37.9 (12.8)	43.6 (18.8)	5.0 (15.4)	0.05
3-D Accuracy	Control	20	70.7 (24.4)	80.0 (21.0)	10.4 (32.2)	0.17
	Comparison	40	69.7 (24.4)	75.8 (20.2)	6.7 (22.6)	0.07
	Intervention ł	40	68.2 (20.8)	77.6 (20.1)	8.7 (24.3)	**0.03**
Orientation Efficiency	Control *	20	42.1 (12.2)	45.8 (11.3)	3.1 (8.8)	0.13
	Comparison ł	40	46.5 (10.6)	61.1 (14.7)	14.6 (10.4)	**0.00**
	Intervention ł	40	44.0 (13.9)	54.6 (18.2)	10.8 (13.1)	**0.00**
Orientation Accuracy	Control	20	86.5 (12.6)	79.5 (14.2)	-6.9 (17.2)	0.09
	Comparison	40	85.9 (9.3)	83.1 (10.6)	-3.3 (11.0)	0.07
	Intervention	40	82.8 (13.3)	83.6 (10.5)	0.8 (11.7)	0.65

***** Statistically significant difference at the 0.05 level between the control group and the other two groups.
ł Statistically significant difference at the 0.05 level between the pretest and the posttest mean scores.

Prior to each test, the researcher emphasized to the participants the importance of accuracy over speed. Accuracy was the primary variable of interest. Therefore, for the purpose of classifying the participants' ability (used to explore relationships for research question 3) as low spatial, average spatial, or high spatial, accuracy in the pretest assessments was used rather than the efficiency scores. Even though a statistically significant difference for accuracy did not exist, the bar chart illustrates interesting patterns (Figure 12). The control, comparison, and intervention group demonstrated equal and moderate gains pre to post in both spatial visualization skills (2-D and 3-D). The gains were statistically significant at a 0.05 level for all groups for the 2-D spatial visualization and for the intervention group for the 3-D visualization. In contrast, the groups demonstrated no change pre to post in spatial orientation skills. The participants became more efficient at orientation—they completed more items in the post than in the pre—but demonstrated no gains in accuracy. This may indicate that spatial orientation skills are more resistant or less malleable than spatial visualization skills. The relatively equal performance in accuracy for the three groups also indicates that gains pre to post were most likely due to the test-retest effect and were not affected by the instructional unit or by the use of maps; digital or otherwise. An independent samples *T* test was used to compare means between males and females. No statistical differences were found. Mean scores on all measures of spatial skill were essentially equal between male and female participants.



* Statistically significant difference at the 0.05 level between the control group and the other two groups.
ᵻ Statistically significant difference at the 0.05 level between the pretest and the posttest mean scores.

Figure 12. Graphic comparison of mean scores of difference by spatial skill test and by group.

QUESTION 2: EFFECT OF GST ON CONTENT KNOWLEDGE

Changes to participants' spatial relations content knowledge was measured with a content test developed specifically for this project and related to the topic of central place theory. The content test had three item categories: content-independent, content-dependent, and task-based items. Content-independent and content-dependent problems were multiple choice items. Task-based items required the students to interpret maps in order to select a "best" location given limiting criteria such as "at least 50 km away from any interstate." Each item category was normalized using a percentage scale. One hundred percent was the maximum possible value and zero percent was the minimum possible value.

Results of the content tests were analyzed by comparing performance of the three instructional groups (control, comparison, and intervention). A taxonomy of spatial thinking created by Jo and Bednarz (2009) was used as a tool to develop items with a high level of spatiality and to assist in creating questions on the posttest that had a similar level of spatiality as the pretest. In addition, the items were aligned with content standards from the Texas Essential Knowledge and Skills (TEKS), spatial operations as described in the *Learning to Think Spatially* (Committee on Support for Spatial Thinking 2006), and spatial relation abilities as described by Golledge and Stimson (1997). Participant responses were coded as correct or incorrect, quantified, and analyzed using descriptive statistics and comparison of means.

A significant difference between the two treatment groups and the control group was found for the content-dependent and independent item categories. No significant difference was present for the task-based items; each group demonstrated substantial loss in scores pre to post on the task-based items. As a result of poor design and match, the task-based items in the posttest were considerably more difficult than the items in the pretest, and thus, the changes in scores do not provide an appropriate comparison. All instructional groups had a significant negative change pre to post in overall (all category types combined) scores. Pretest scores, posttest scores, and mean difference scores were compared for the three groups using an independent T test. The variance was similar for the groups, allowing an appropriate comparison of their means using independent samples T test. No significant differences existed between the two treatment groups in pretest scores or posttest scores for any category on the spatial relations content test.

Both treatment groups' pre to post content knowledge scores increased, but only the intervention group showed statistically significant gains, a 15.0 percent ($p = 0.01$) increase in content-independent items and a 11.9 percent ($p = 0.05$) increase in content-dependent items. In addition to testing for statistical significance, Cohen's d was calculated to estimate effect sizes and to compare degree of impact between the comparison group and intervention group. Cohen's d is the difference between the mean scores pre to post divided by the pooled standard deviation. The effect sizes for the intervention group were larger than the effect sizes for the comparison group: 0.54 and 0.30 for the content-independent item category, 0.47 and 0.26 for the content-dependent item category, respectively. The content-dependent items appear to have been more difficult than the content-independent items because both treatment groups demonstrated greater mean gains in the content-independent category. A 2.5-week delay between the activity and the posttest was planned in an effort to measure content acquired and retained rather than content recognition or familiarity. Table 8 summarizes the descriptive statistics and comparison of means by instructional group for the spatial relations content test.

Table 8. Summary of spatial relations content test by instructional group.

		n	Pre Mean (std)	Post Mean (std)	Mean Difference	Sig.
Overall	Control * ɪ	20	43.2 (19.4)	25.0 (16.4)	-19.3	**0.00**
	Comparison ɪ	41	51.4 (16.7)	38.7 (18.3)	-12.4	**0.00**
	Intervention ɪ	41	50.5 (17.7	41.2 (19.6)	-9.9	**0.01**
Content-independent	Control *	20	53.9 (28.6)	43.3 (34.7)	-12.7	0.11
	Comparison	41	57.1 (25.2)	65.0 (27.8)	8.5	0.13
	Intervention ɨ	41	56.7 (25.0)	71.5 (29.4)	15.0	**0.01**
Content-dependent	Control * ɪ	20	36.2 (21.7)	25.0 (23.3)	-27.0	**0.05**
	Comparison	41	39.3 (17.6)	44.9 (24.8)	5.9	0.19
	Intervention ɨ	41	39.5 (23.9)	51.7 (28.3)	11.9	**0.05**
Task-based	Control ɪ	20	37.5 (30.5)	15.0 (22.2)	-22.5	**0.01**
	Comparison ɪ	41	56.1 (28.6)	25.2 (27.4)	-30.9	**0.00**
	Intervention ɪ	41	54.1 (32.0)	15.4 (22.8)	-38.6	**0.00**

***** Statistically significant difference at the 0.05 level between the control group and the other two groups.
ɪ Statistically significant negative difference at the 0.05 level between the pretest and the posttest mean scores.
ɨ Statistically significant positive difference at the 0.05 level between the pretest and the posttest mean scores.

Spatial relations content test scores were compared by sex. The control group was removed, and only the treatment groups were analyzed for sex differences. No difference was found between males and females for pretest scores or posttest scores. Males and females showed gains pre to post in the content-independent and content-dependent categories. Only males, however, showed a significant gain in one category: content-independent. Table 9 summarizes descriptive statistics and comparison of means by sex for the two instructional groups.

Table 9. Summary of spatial relations content test by sex (comparison and intervention groups).

		n	**Pre Mean (std)**	**Post Mean (std)**	**Mean Difference**	**Sig.**
Content-independent	Male ł	42	57.1 (23.6)	69.8 (28.3)	12.7	**0.02**
	Female	40	56.0 (26.9)	66.7 (29.2)	10.7	0.06
Content-dependent	Male	42	39.7 (21.1)	48.1 (24.6)	8.4	0.09
	Female	40	39.2 (21.2)	48.5 (29.0)	9.3	0.10

ł Statistically significant positive difference at the 0.05 level between the pretest and the posttest mean scores.

Positive gains in content knowledge were evident in both treatment groups as compared to the control group. Only the intervention group, however, demonstrated significant gains pre to post. These results suggest that using GST for teaching and learning has a greater positive effect on students' content knowledge of a spatial concept in geography than using an alternative, more traditional, approach. Another consideration, however, is the large standard deviations in each group. The large variations suggest factors other than choice of instructional method are influencing performance. The scores of some individuals did not improve using GST, some individuals did significantly worse. The large standard deviations were also present in the comparison group who used paper maps. Further examination of the relationships among the students' spatial visualization and orientation skills compared to their changes in skills and content knowledge based on the instructional method were analyzed to explore the best methods of practice and representation for students with different levels of spatial thinking skills.

QUESTION 3: RELATIONSHIPS AMONG SPATIAL SKILL LEVEL, SELF-ATTITUDES, AND CONTENT KNOWLEDGE

Categories Based on Spatial Skill Level

Participants were categorized based on their starting spatial skill level, as measured in the pretests, into three spatial skill groups: low spatial, average spatial, and high spatial. The influence of starting spatial skill level, sex, and method of instruction on gains in content knowledge was explored, using correlations and analysis of variance (ANOVA).

Prior to categorization, Pearson's Correlation Coefficient was used to determine the measure of strength and significance of the relationship for pretest values of accuracy in the three spatial skills measured. The analysis indicated a positive correlation that is significant but weak for all three spatial skill tests (Table 10).

Table 10. Correlations for spatial skills prescores

		Pre-2D Accuracy (%)	Pre-3D Accuracy (%)	Pre-Orientation Accuracy (%)
Pre-2D Accuracy (%)	Pearson Correlation	1	.211	.406
	Sig. (2-tailed)		.024	.000
	N	114	114	109
Pre-3D Accuracy (%)	Pearson Correlation		1	.190
	Sig. (2-tailed)			.048
	N		119	109
Pre-Orientation Accuracy (%)	Pearson Correlation			1
	Sig. (2-tailed)			
	N			109

Because the scores were positively correlated and results of pretests for groups were very similar based on sample size, starting point, and variance; the pretest scores for spatial skills were combined and an average score was used to divide individuals into spatial skill categories. This is not to argue that two-dimensional visualization, three-dimensional visualization, and spatial orientation are a single skill. An emerging body of evidence from behavioral sciences and neuroscience suggests that these processes are physiologically and behaviorally distinct (Zacks and Tversky 2005; Hegarty et al. 2006). In this study, however, the scores were aggregated to represent one measure for spatial skills because, in general, a relatively higher than average score on one measure was associated with a relatively higher than average score on the other two.

For the purpose of defining spatial skill categories, the measure of test accuracy was selected. Accuracy most likely reflects individuals' starting spatial skill level without an advantage to males based on efficiency. In prior studies examining sex differences in spatial skills, females performed equal to males when time was not a factor in the assessment. In other words, females were as accurate as males in solving spatial problems, but they were not as fast (Casey 1996; Linn and Peterson 1985, Masters and Sanders 1993). Using a histogram and frequency table of the aggregated scores for accuracy, three categories were created and labeled low spatial, average spatial, and high spatial. The categories were determined by subdividing the distributions at equal distances from the mean. The mean was 81.9 percent. The break between low and average was 76.5 percent; the break point between average and high occurred at 88.5 percent, providing a span of 12 percentage points (Figure 13).

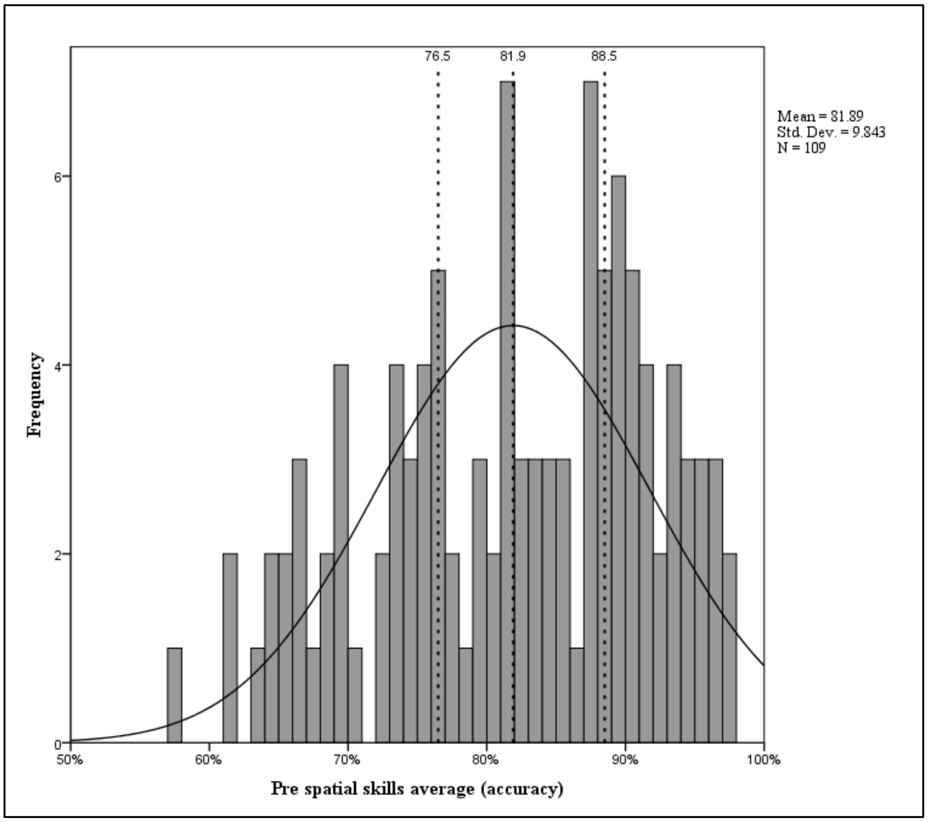


Figure 13. Distribution of spatial skill scores

This grouping of participants by spatial skill level resulted in a relatively equal distribution of males and females in each category. The low spatial group contained an equal number of males and females (n=18), the average spatial group had three more females than males, and the high spatial group had four more males than females. Chi-square analysis indicated no significant difference in the count for males and females in the three spatial skill groupings (p = 0.712). Comparison of the number of males and females by spatial skill category are summarized in Table 11.

Table 11. Crosstabulation of males and females by spatial skill category.

Spatial Skill Category		Sex		
		Male	Female	Total
	Low Spatial	18	18	36
	Average Spatial	17	20	37
	High Spatial	20	16	36
Total		55	54	109

The distribution of participants after they were grouped into category by spatial skill level proved to be relatively equal for the three instructional groups (control, comparison, and intervention). Equal numbers of low spatial participants were present in the comparison and intervention groups. One additional average spatial participant was in the intervention group than in the comparison. And, three additional high spatial participants were in the comparison group than in the intervention group. Chi-square analysis indicates no significant difference in the counts for the intervention and comparison groups with respect to the three spatial skill groupings ($p = 0.812$). The number of participants present at the pretest phase, which the spatial skill categorization is based upon, does not equal the number of participants that completed all phases of the study. Because of absences and other factors, only 102 of the 109 students who started the project completed all phases. Comparison of the number of participants in the three instructional groups tabulated by spatial skill category is summarized in Table 12 and illustrated in Figure 14.

Table 12. Crosstabulation of participants in instructional group by spatial skill category

Spatial Skill Category		**Instructional Group**			
		Control	Comparison	Intervention	Total
	Low Spatial	6	15	15	36
	Average Spatial	9	12	16	37
	High Spatial	8	15	12	35
Total		23	42	43	108

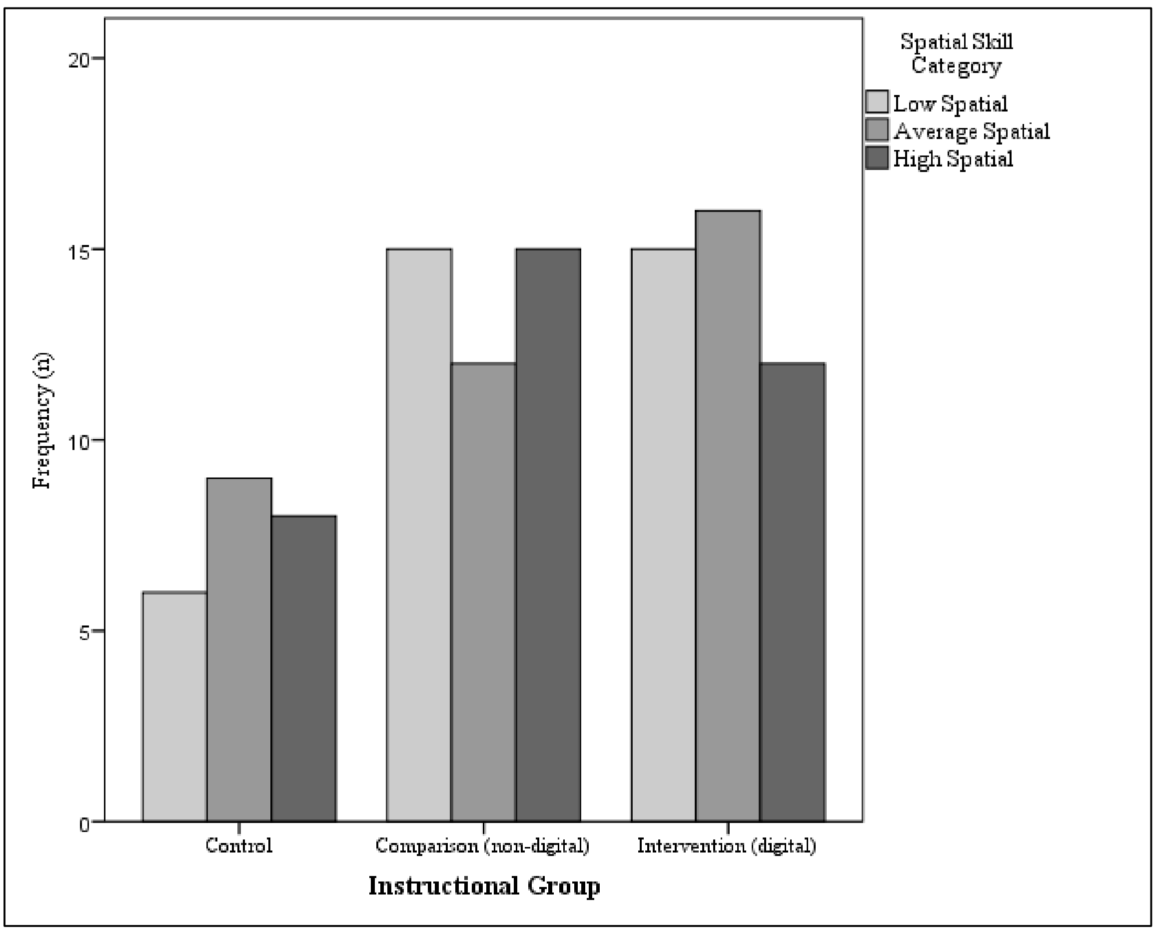


Figure 14. Participants in instructional group by spatial skill category

Changes to Spatial Skills by Spatial Skill Category

Examining pre and post accuracy scores for spatial skills, several interesting relationships between spatial skill category and performance emerge. The high, average, and low category scores are consistently high, average, and low on the pretests for all three of the spatial skills measured. In addition, a statistically significant difference among all three group pretest scores for 2-D and 3-D visualization and a significant difference between the high spatial group and the other two groups in orientation skills was found. These patterns in the pretest scores add further support for the method used to establish the spatial skill categories.

The low spatial group showed the largest gains in pre to post for 2-D and 3-D visualization skills (9.1 percent gain, p=0.00, and 21.7 percent gain, p=0.00, respectively). The average spatial group also had statistically significant gains pre to post for 2-D and 3-D visualization skills (5.9 percent gain, p=0.00, and 8.0 percent, p=0.03, gain respectively). None of the three groups evidenced improvement in spatial orientation.

The high spatial group made very little, if any, gains in accuracy on any of the three spatial skills tests perhaps because of a ceiling effect. In addition, because the different measures are correlated, a carry-over effect may be present for the three measures (Schwonke et al. 2011). In other words, gains observed in the low spatial group may be a result of the combination of practice on the three assessments. It is difficult to conclude that gains in spatial skills can be attributed to the intervention because the control group gained as much (or as little) as the treatment groups.

Even though the low spatial group made the largest gains in 2-D and 3-D spatial skills, they scored significantly lower on average on the posttest scores compared to the average and high spatial groups. Comparing posttest scores using an independent samples T test, the low spatial group's mean score remained significantly lower for 2-D and 3-D visualization (p=0.00). On the other hand, even though the high spatial group had a decrease in orientation scores, their posttest scores remained significantly higher than the low and average spatial groups (p=0.01 and p=0.03, respectively).

Significant gains were made pre to post in the low and average spatial groups for 2-D and 3-D visualization. Table 13 summarizes pre and post scores of spatial skills by spatial skill group. Figure 15 illustrates changes pre to posttest for the three spatial skill groups.

Table 13. Summary of mean spatial skill test scores (%) by spatial skill group.

		n	Pre Mean (std)	Post Mean (std)	Mean Difference	Sig.
2-D Accuracy	Low spatial ǂ	32	72.5 (16.9)*	81.6 (14.7)*	9.10	**0.00**
	Average spatial ǂ	37	83.5 (11.9)*	89.4 (8.5)	5.90	**0.00**
	High spatial	32	91.1 (5.8)*	93.6 (9.6)	2.50	0.18
3-D Accuracy	Low spatial ǂ	32	44.3 (14.3)*	66.0 (21.1)*	21.70	**0.00**
	Average spatial ǂ	37	71.9 (12.2)*	79.9 (18.9)	8.00	**0.03**
	High spatial ɪ	32	92.0 (8.3)*	86.1 (14.7)	-5.90	**0.03**
Orientation Accuracy	Low spatial	32	80.7 (12.2)	80.4 (12.1)	-0.30	0.76
	Average spatial	37	83.7 (13.1)	80.7 (12.6)	-3.00	0.22
	High spatial	32	90.3 (7.0)*	87.4 (11.7)*	-2.90	0.14

***** Statistically significant difference at the 0.05 level between the noted group and the other groups for the same test.

ɪ Statistically significant negative difference at the 0.05 level between the pretest and the posttest mean scores.

ǂ Statistically significant positive difference at the 0.05 level between the pretest and the posttest mean scores.

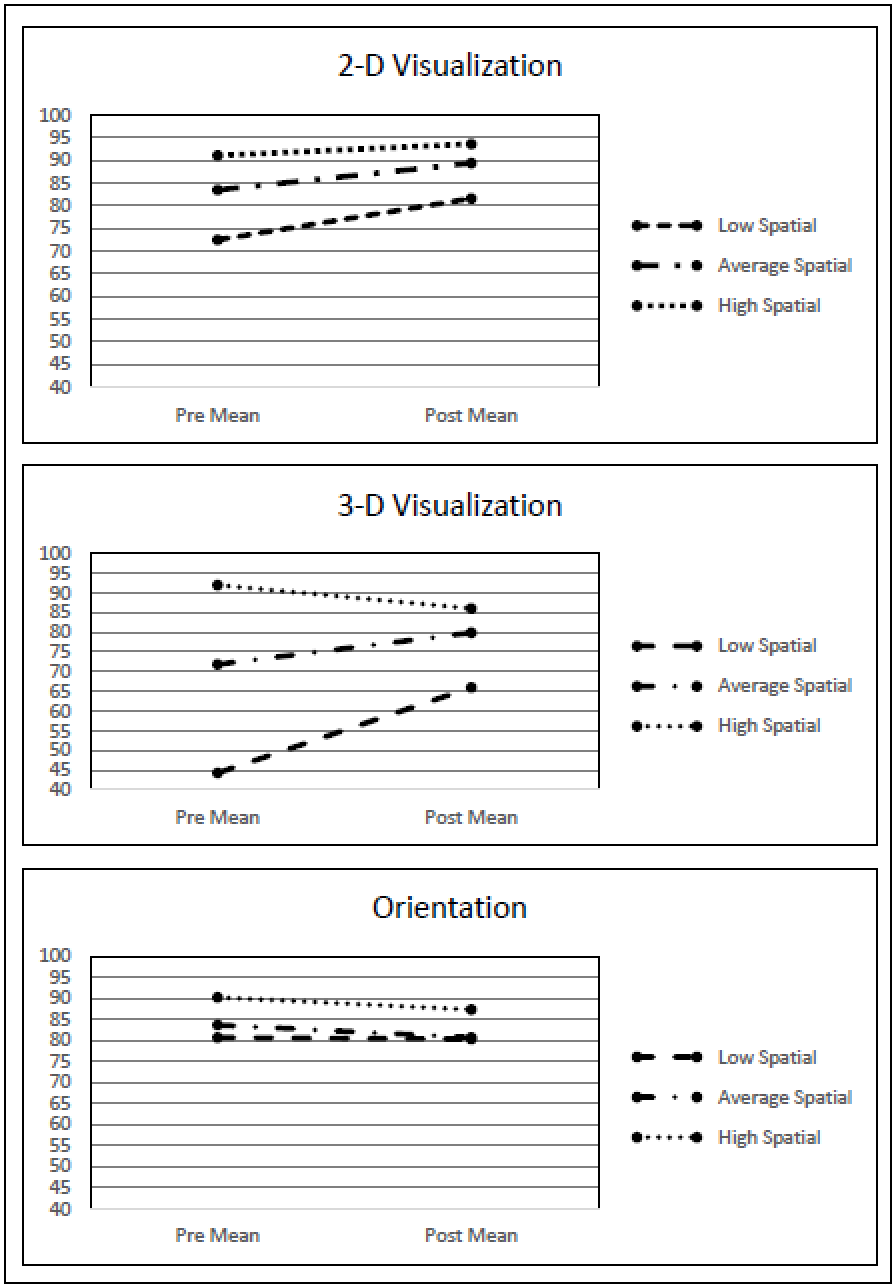


Figure 15. Pre to post changes for spatial skills by spatial skill group

Changes to Content Knowledge by Spatial Skill Category

Comparison of the instructional groups' spatial relations content knowledge, as measured by the spatial relations content test, indicates that the digital instructional style using GST was the most effective method to significantly increase participants' content-dependent and content-independent scores pre to post intervention. However, a more complex pattern emerges when examining changes to content knowledge based on starting spatial skill level.

Questions in the content test were divided into three categories: content-independent, content-dependent, and task-based items. The second task-based item in the posttest was considerably more difficult than the second item in the pretest and thus does not provide an appropriate comparison and is not considered here. Considering, then, only pre to post gains in content-independent questions and content-dependent questions, trends were explored based on spatial skill categories and intervention group (digital) and the comparison group (non-digital). The control group received no instruction about central place theory nor did they show any gains in spatial relations content knowledge, therefore, they were excluded from further analysis examining change in content knowledge.

All three spatial skill groups gained in the content-independent knowledge. Only the high spatial group, however, demonstrated significant gains (15.4 percent gain, p=0.02). In the content-dependent item category, no change was discovered for the low spatial participants and only a small gain (5.1 percent) for the average spatial participants was detected. Similar to the content-independent item category, only the high spatial group demonstrated significant gains in the content-dependent knowledge (23.1 percent gain, *p*=0.00). The standard deviations for the three groups and for both item categories were very large. Thus, Cohen's d was calculated in order to compare effect size in addition to statistical significance. Instruction appears to have had little to no effect on spatial relations content knowledge for the low spatial group. The average spatial group demonstrated a medium effect size for the content-independent item category (d=0.43), and a small effect size for content-dependent (d=0.21). The high spatial group demonstrated a medium effect from instruction for content-independent and a large effect for content-dependent (d=0.68 and d=1.03, respectively). Table 14 summarizes pre and post scores of spatial relations content knowledge by spatial skill group.

Table 14. Summary of mean spatial relations content test scores (%) by spatial skill group.

		n	Pre Mean (std)	Post Mean (std)	Mean Diff.	Sig.	d
Content-independent	Low spatial	29	54.7 (26.7)	63.2 (36.0)	8.5	0.24	0.27
	Average spatial	28	57.1 (25.4)	67.9 (24.8)	10.8	0.06	0.43
	High spatial ł	25	59.3 (23.2)	74.7 (22.1)	15.4	**0.02**	0.68
Content-dependent	Low Spatial	29	40.6 (21.3)	40.7 (25.3)	0.1	0.94	0.00
	Average spatial	28	39.9 (21.9)	45.0 (26.5)	5.1	0.42	0.21
	High spatial ł	25	37.7 (19.9)	60.8 (24.8)*	23.1	**0.00**	1.03

***** Statistically significant difference at the 0.05 level between the noted group and the other groups for the same test.
ł Statistically significant positive difference at the 0.05 level between the pretest and the posttest mean scores.

Influence of Instructional Group to Changes in Content Knowledge by Spatial Skill Category

Thus far, results support the premise that teaching spatially-dependent concepts, such as central place theory, using GST increases spatial relations content knowledge more than teaching with a static, traditional, paper-and-pencil method. In addition, results indicate that individuals possessing high spatial skill acquire spatial relations content knowledge better and/or faster than individuals of low or average spatial skill. The interaction between individuals' spatial skill level and instructional method, and the impact that interaction may have on spatial relations content knowledge is explored by adding an additional level of analysis; instructional group by spatial skill group (2 X 3).

Utilizing a paired T test to compare pre and posttest results, large and significant gains in spatial relations content knowledge were observed for the high spatial intervention group. For the content-independent category items, the high spatial intervention group improved by 28.1 percent ($p=0.01$), and for the content-dependent category items by 35.4 percent ($p=0.01$). Even though the high spatial comparison group had large and significant gains in the content-dependent item category, the gains were less than that observed in the intervention group (21.9 percent difference in gains, p=0.26). No other groups had statistically significant gains pre to post. Calculating the effect size, however, several other groups demonstrated medium, albeit insignificant, gains. Notably, the average spatial comparison group showed consistent medium-sized positive effects on both item categories (d=0.66 and 0.62).

Pretest scores were analyzed for the six groups to explore potential violations of assumptions (e.g., equal variance, similar starting point, semi-equal sample size). All groups had similar means prior to instruction with the exception of the average spatial group. In the content-dependent pretest, the average spatial intervention group had a statistically higher mean than the average spatial comparison group (46.9 percent versus 30.6 percent, p=0.04). However, in the posttest, the average spatial comparison group gained substantially more than their counterparts in the intervention group although no significant difference was evident between the two in the post test scores.

Analysis of variance (ANOVA) was used to compare posttest results for spatial skill groups. The high spatial scored significantly better than the low spatial group for the content-dependent item category (55.7 percent versus 36.0 percent, p=0.03) and better than the intervention group for the content-independent item category (84.8 percent versus 61.9 percent, p=0.04). A comparison of scores for high spatial in the intervention group versus the comparison group demonstrates the high spatial intervention group scored significantly higher on the content-independent item category posttest than the high spatial comparison group (84.8 percent versus 66.7 percent, p=0.03).

Overall, when comparing participant groups by both spatial skill level and instructional method, the high spatial individuals in the instructional group utilizing GST gained the most in spatial relations content knowledge. Table 15 summarizes the results of the analysis of spatial relations content knowledge by instructional group and spatial skill group. Figure 16 and Figure 17 illustrate the mean difference between pretest and posttest scores for the two item categories.

Table 15. Summary of mean spatial relations content test scores (%) by instructional group and spatial skill group.

			n	Pre (std)	Post (std)	Mean Diff.	Sig.	d
Comparison	Content-independent	Low	15	58.7 (25.6)	64.4 (38.8)	5.7	0.60	0.18
		Average	12	50.0 (24.9)	63.9 (17.2)	13.9	0.13	0.66
		High	14	61.3 (25.6)	66.7 (22.6)§	5.4	0.48	0.22
	Content-dependent	Low	15	43.3 (20.7)	36.0 (24.1)*	-7.3	0.30	-0.33
		Average	12	30.6 (15.6)§	43.3 (25.3)	12.7	0.19	0.62
		High ɫ	14	42.2 (13.9)	55.7 (22.4)*	13.5	**0.05**	0.74
Intervention	Content-independent	Low	14	50.7 (28.1)	61.9 (34.2)*	11.2	0.29	0.36
		Average	16	62.5 (25.2)	70.8 (29.5)	8.3	0.26	0.30
		High ɫ	11	56.7 (20.6)	84.8 (17.4)*§	28.1	**0.01**	**1.48**
	Content-dependent	Low	14	37.8 (22.2)	45.7 (26.5)	7.9	0.41	0.32
		Average	16	46.9 (23.7)§	46.3 (28.0)	-0.6	0.94	-0.02
		High ɫ	11	31.9 (25.1)	67.3 (27.2)	35.4	**0.01**	**1.35**

***** Statistically significant difference at the 0.05 level between the high spatial and the low spatial group in the same instructional group for the same test.
§ Statistically significant difference at the 0.05 level between the intervention and comparison group in the same spatial skill group for the same test.
ɫ Statistically significant positive difference at the 0.05 level between the pretest and the posttest mean scores.

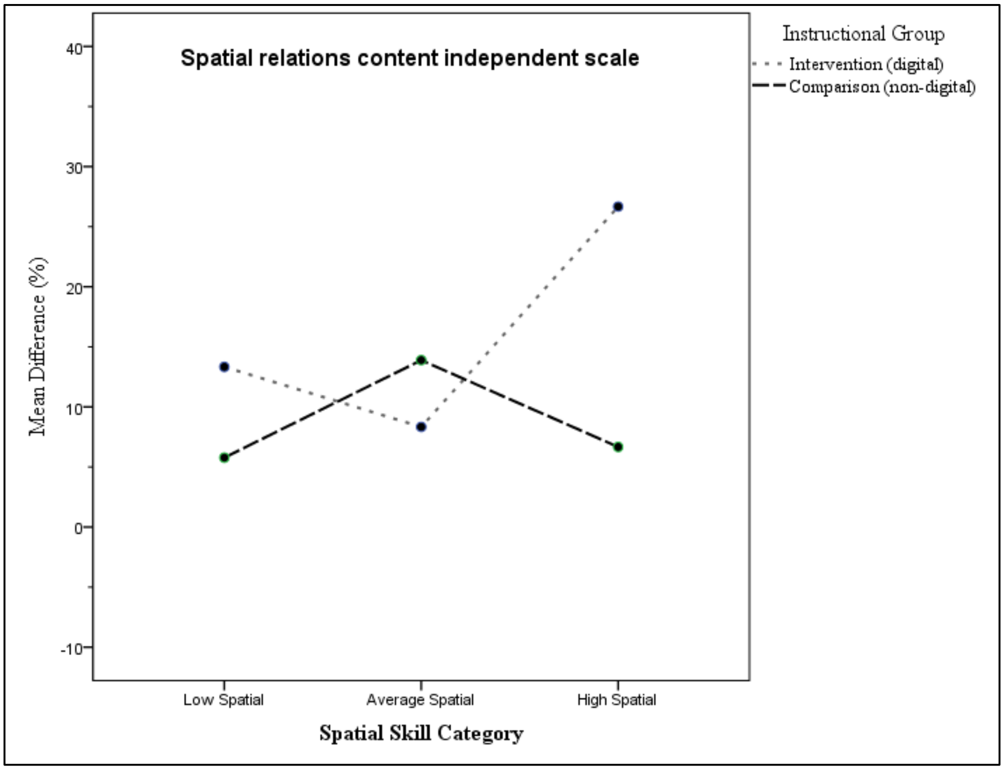


Figure 16. Mean difference pretest to posttest for spatial relations content-independent item category by instructional group and spatial skill group.

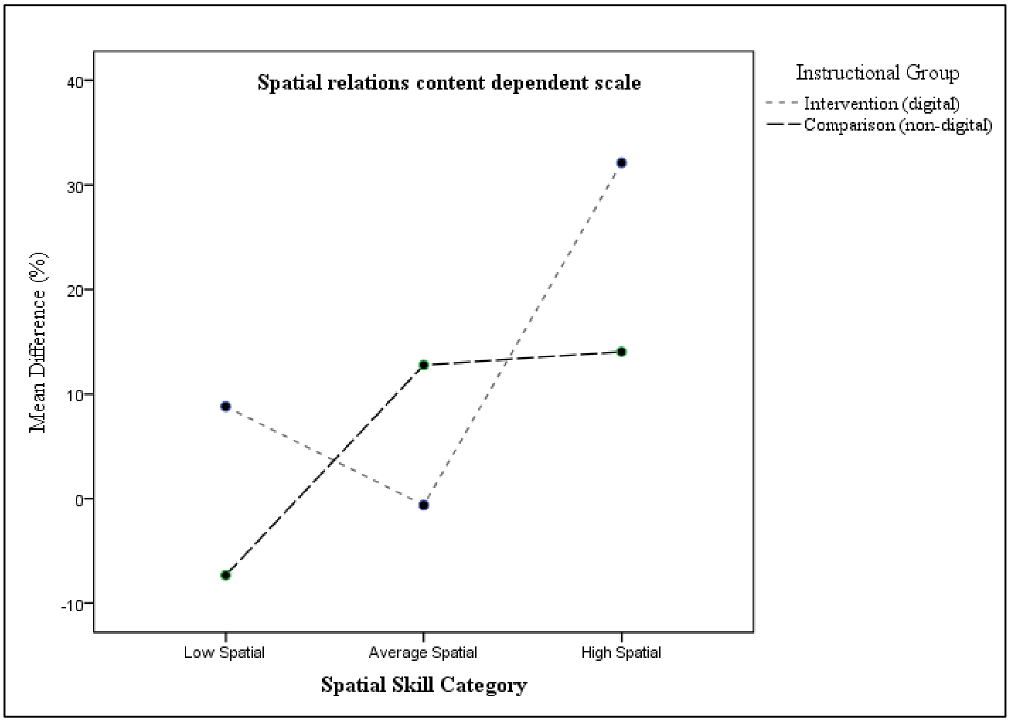


Figure 17. Mean difference pretest to posttest for spatial relations content-dependent item category by instructional group and spatial skill group

Influence of Sex to Changes in Content Knowledge by Spatial Skill Group and Instructional Group

Sex-related differences are frequently found in spatial skills. On many spatial tasks such as 3-dimensional rotation and mechanical abilities, males perform consistently and significantly better than females (Linn and Peterson 1985). Expecting to find sex-related differences in the pre spatial skills, mean scores for males and females for each spatial skill were examined. No significant differences were evident in the pretest scores. Likewise, male and female posttest scores did not reveal sex-related differences in gains or in final scores. However, when grouped by spatial skill category, sex differences were present in the spatial relations content test. The interaction between individuals' sex, spatial skill level, and instructional method, and the impact those interactions may have had on spatial relations content knowledge, was explored by adding an additional level of analysis; (2 X 3 X 2) instructional group (intervention or comparison) by spatial skill group (low, average, or high) by sex (male or female).

Pretest scores were analyzed for the twelve sub-groups to explore potential violations of assumptions (e.g., equal variance, similar starting point, semi-equal sample size). All groups had similar means prior to instruction with the exception of the high spatial males. The high spatial males in the comparison group scored significantly better on the content-independent pretest than high spatial males in the intervention group (66.7 percent versus 45.7 percent, p=0.04). However, on the posttest, the trend reversed. High spatial males in the intervention group not only made significant gains pre to post, they significantly outperformed high spatial males in the comparison group (88.9 percent versus 62.5 percent, p=0.05).

Independent T tests were used to compare males and females on posttest spatial skill level and instruction. Only for the males in the intervention group was there a statistical difference between the low and high spatial groups. High spatial males outperformed low spatial males in both content-independent and content-dependent item categories. The high spatial intervention group males scored significantly higher on the content-independent posttest than those in the comparison group. In addition, low spatial intervention group females significantly outperformed those in the comparison group on the content-dependent item category (52.5 percent versus 25.7 percent, p=0.05).

Changes in content knowledge for each spatial skill group by sex were analyzed utilizing a paired T test to compare pre and posttest results. The low spatial skill group showed no significant gains in content knowledge for either the content-independent or content-dependent item categories regardless of instructional method. Yet, differences by sex were evident. Low spatial skill males had large but insignificant gains in the comparison group on the content-independent item category (19.2 percent gain, d=0.74), whereas low spatial females decreased by 9.5 percent. Both low spatial skill males and females decreased pre to post in the comparison group on the content-dependent item category. Their counterparts in the intervention group had opposite results. The low spatial skill females demonstrated large gains in both content-independent and -dependent item categories (25.0 and 17.1 percent, respectively), whereas the low spatial males in the intervention group had a decrease in both (10.9 and 4.1 percent).

The average spatial skill group showed no significant gains in content knowledge for either the content-independent or dependent item categories regardless of instructional method. Here, too, sex differences were evident. Average spatial skill males in the comparison group demonstrated no change on the content-independent item category but a large, although insignificant, gain on the content-dependent item category (20.8 percent, d=1.00). Average spatial females in the comparison group demonstrated large and medium, statistically insignificant, gains in both the content-independent and dependent item categories (21.7 percent and 8.7 percent, respectively). For the intervention group, average spatial skill males demonstrated no change in the content-dependent item category but a large, again insignificant, gain in the content-independent item category (16.7 percent, d=0.66). Average spatial skill females in the intervention group had a small decrease in scores pre to post for both unlike what was observed for the comparison group.

Large and significant gains in spatial relations content knowledge were found for high spatial males and females in the intervention group. Males demonstrated significant gains in the content-independent item category (43.2 percent, *p*=0.00), and, although not statistically significant, also had large gains in the content-dependent item category (33.8 percent, d=1.22). Females in this group demonstrated medium gains in the content-independent item category (8.0 percent, d=0.44), and, large significant gains in the content-dependent item category (33.0 percent, *p*=0.05). No other groups had statistically significant gains pre to post.

Averages can hide variation. Prior to dividing the participants by spatial skill level, no pattern of advantage based on instructional method between males and females was evident. After categorizing and analyzing individuals by initial spatial skill level, substantial differences for males and females were evident. For example, low spatial males in the comparison group improved by 19.2 percent (d=0.74) pre to post on the content-independent item category. Low spatial skill females in the same instructional group decreased by 9.5 percent. When males and females were considered together, the differences in gains averaged out to a mean gain of 5.7 percent, hiding this variation.

Low spatial skill males were found to benefit slightly from the non-digital method of instruction, whereas low spatial skill females in the intervention group performed better with the GST approach. Results for average spatial skill males did not indicate an advantage for either instructional method, whereas for average spatial skill females, using a non-digital method of instruction produced large score improvements. For the high spatial skill group, using GST makes a large difference for males who performed better on both item categories. High spatial skill females demonstrated positive gains in content knowledge for all instructional methods.

In general, when comparing males and females by instructional group and spatial skill level, high spatial males and females drive the significant gains shown by the intervention group. High spatial individuals consistently outperform low and average spatial individuals, and the advantage is larger for the intervention group than for the comparison group. The link between thinking spatially and thinking geographically is noticeable. Higher levels of spatial thinking are correlated with a superior ability for thinking geographically.

These results infer that neither males nor females had an advantage based on sex for performance on the spatial relations content test. Likewise, in the low and average spatial skill groups, there does not appear to be an advantage to performance on the spatial relations test based on type of instructional method. However, trends indicate large variations in academic performance and influence of instructional method due to sex and spatial skill level. Table 16 summarizes the results of the analysis of spatial relations content knowledge by instructional group, sex, and spatial skill group.

Table 16. Summary of mean spatial relations content test scores (%) by instructional group, sex, and spatial skill group.

				n	Pre Mean (std)	Post Mean (std)	Mean Difference	Sig.	Cohen's d
Comparison	Male	Content-independent	Low	8	60.0 (21.4)	79.2 (30.5)	19.2	0.16	0.74
			Average	4	60.0 (23.1)	58.3 (16.7)	-1.7	0.87	-0.09
			High	8	66.7 (20.0)§	62.5 (27.8)§	-4.2	0.83	-0.18
		Content-dependent	Low	8	47.9 (13.9)	45.0 (25.6)	-2.9	0.79	-0.15
			Average	4	29.2 (16.0)	50.0 (25.8)	20.8	0.12	**1.00**
			High	8	40.7 (14.7)	52.5 (21.2)	11.8	0.14	0.66
	Female	Content-independent	Low	7	57.1 (31.5)	47.6 (42.4)	-9.5	0.60	-0.26
			Average	8	45.0 (25.6)	66.7 (17.8)	21.7	0.10	**1.00**
			High	6	53.3 (32.7)	72.2 (13.6)	18.9	0.28	**0.82**
		Content-dependent	Low	7	38.1 (26.7)	25.7 (19.0)§	-12.4	0.18	-0.39
			Average	8	31.3 (16.5)	40.0 (26.2)	8.7	0.52	0.41
			High	6	44.4 (13.6)	60.0 (25.3)	15.6	0.24	**0.80**
Intervention	Male	Content-independent	Low	6	51.4 (30.2)	40.5 (18.9)*	-10.9	0.92	-0.44
			Average	10	60.0 (28.3)	76.7 (22.5)	16.7	0.11	0.66
			High ł	6	45.7 (15.1)§	88.9 (17.2)*§	43.2	**0.00**	**2.67**
		Content-dependent	Low	6	40.8 (18.9)	36.7 (23.4)*	-4.1	0.86	-0.19
			Average	10	45.0 (26.1)	46.0 (26.7)	1.0	0.93	0.04
			High	6	26.2 (27.0)	60.0 (28.3)*	33.8	0.10	**1.22**
	Female	Content-independent	Low	8	50.0 (28.3)	75.0 (29.5)	25.0	0.11	**0.87**
			Average	6	66.7 (20.7)	61.1 (39.0)	-5.6	0.58	-0.19
			High	5	72.0 (17.9)	80.0 (18.3)	8.0	0.41	0.44
		Content-dependent	Low	8	35.4 (25.9)	52.5 (28.2)§	17.1	0.32	0.63
			Average	6	50.0 (21.1)	46.7 (32.7)	-3.3	0.83	-0.12
			High ł	5	40.0 (22.4)	76.0 (26.1)	36.0	**0.05**	**1.48**

***** Statistically significant difference at the 0.05 level between the high spatial and the low spatial group in the same sex and instructional group.
§ Statistically significant difference at the 0.05 level between the intervention and comparison group in the same sex and spatial skill group for the same test.
ł Statistically significant positive difference at the 0.05 level between the pretest and the posttest mean scores.

Figure 18 and Figure 19 illustrate the mean difference and confidence intervals for pretest and posttest scores for the two spatial relations categories using a clustered error bar graph. A clear distinction, with no overlap, is discernable between the pre and post error bars in the intervention group for high spatial males in the content-independent item category. The distinction is less evident for high spatial females in the same instructional group. Even though the overall gain was substantial, the extremely large standard deviations in the high spatial female group, illustrated by the error bars, indicate remaining variation among the five females that made up this group.

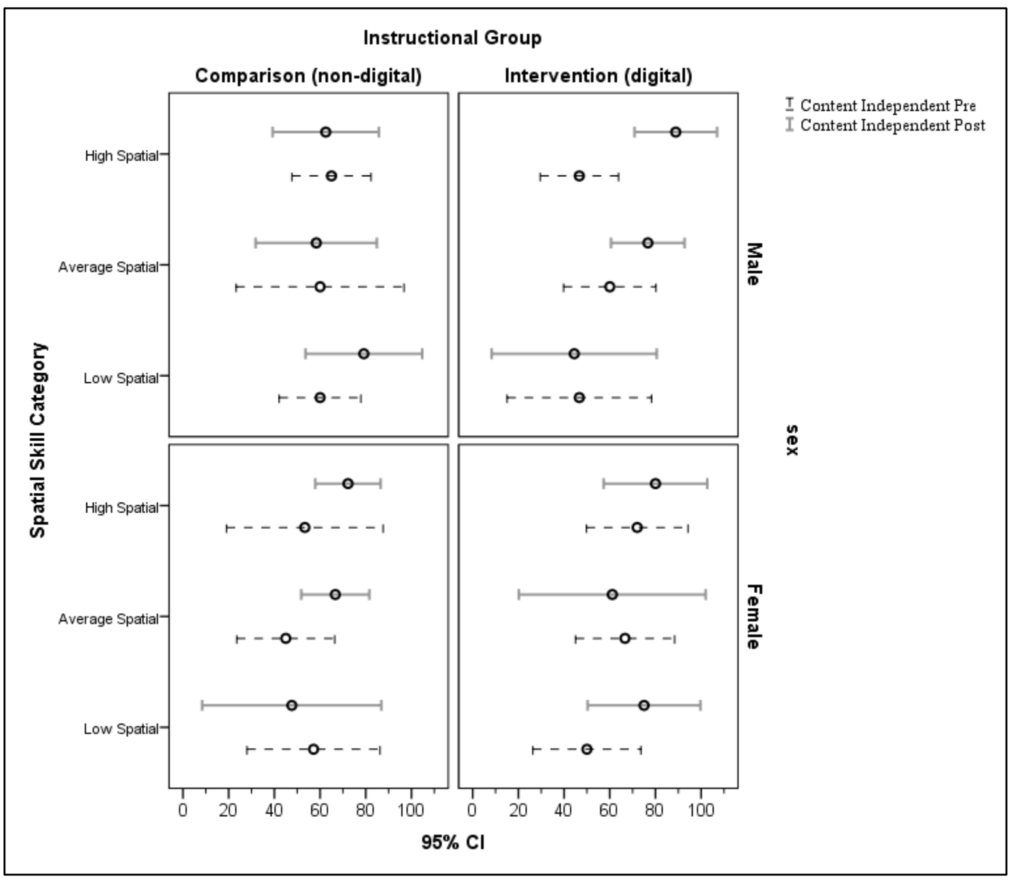


Figure 18. Clustered error bar graphs for the spatial relations content-independent item category.

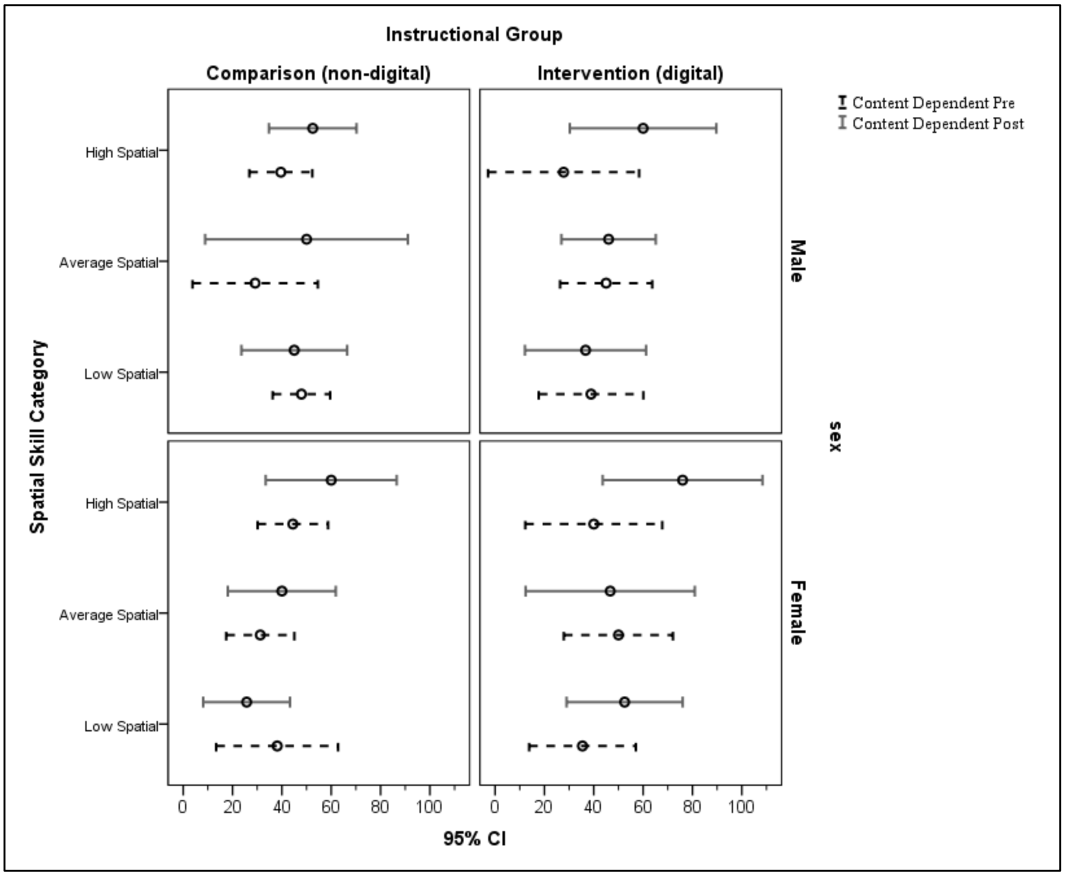


Figure 19. Clustered error bar graphs for the spatial relations content-dependent item category.

Relationship Between Gains in Spatial Skill and Gains in Spatial Relations Content Knowledge

High spatial skill level positively affects gains in spatial relations content knowledge. Gains in spatial skills were obtained through training and were evident in this study from a test-retest effect. It is feasible that gains in spatial skills may be correlated to gains in spatial relations content knowledge. In other words, individuals that demonstrated gains in spatial skills may also have developed an advantage in spatial relations.

This possible correlation was explored using a scatterplot graph and Pearson correlation coefficient (r). First, participants that had improved pretest to posttest on combined spatial skills accuracy by 10 percent or more were identified. Second, the control group was removed. Considering only individuals that had demonstrated gains in spatial skills and had received instruction on central place theory, correlation between gains in spatial skills and gains in spatial relations were explored.

No relationship existed ($r = -0.17$, $p = 0.457$). As is illustrated in the scatter plot graph (Figure 20), participants with the greatest gains in spatial skill had little to no gains in spatial relations. With no discernable pattern, the highest gains in spatial relations were achieved by a few participants with the least percentage spatial skill gain considered for this group (10 percent). Content relations scores for the majority of individuals (14 out of 21) either decreased or remained unchanged regardless of gains in spatial skill.

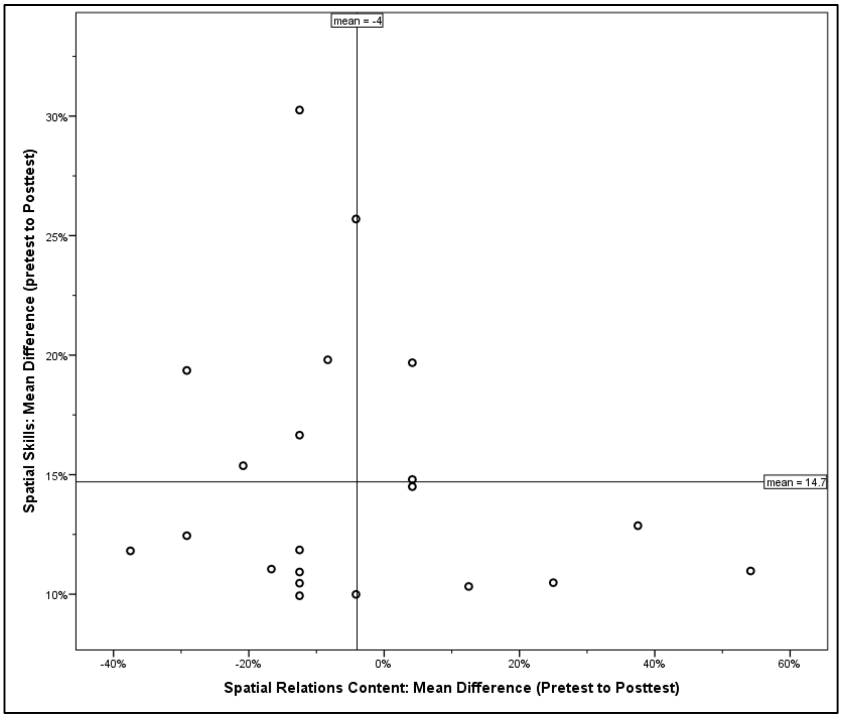


Figure 20. Scatterplot graph illustrating no relationship between spatial skill gains and spatial relation gains.

Results of the Spatial Survey

A modified version of the Santa Barbara Sense of Direction survey was created for this study. It contained 17 questions that asked individuals to self-report, on a six-point Likert scale, their navigational abilities, preferences, and experiences. Questions reflected self-efficacy for tasks such as giving directions, judging distances, and reading maps. Out of the 17 items, eight were negative statements that reflect a lack of confidence or self-efficacy related to navigation and sense of direction (items #2, 6, 8, 10, 11, 12, 13, and 15) while 9 items were positive (items #1, 3, 4, 5, 7, 9, 14, 16, and

17). Participating students (n=109) completed the spatial survey prior to instruction during the pretesting phase.

Descriptive results from the spatial survey are reported followed by explanation of the method used to identify dominant factors in the spatial survey; description of the self-efficacy spatial survey categories; and exploration of correlations and relationships among the self-efficacy spatial survey categories, spatial skills, and spatial relations content knowledge.

Internal reliability for the 17-item survey was acceptable (r = 0.78). Overall, participants were confident in their skills to read maps, give directions, and judge distances. Confidence, however, does not translate to desire. Many of the participants (n=40) agreed or strongly agreed they were good at giving directions, yet only 13 (12 percent) volunteer to do the navigational planning for long trips. A large majority (n=89, 82 percent) agreed or strongly agreed they "tend to think visually, with lots of mental images" and believe they have a good "mental map" of their environment (n=66, 61 percent). Only 12 (11 percent), however, reported that they tend to think of their environment in terms of cardinal directions. Research indicates individuals with survey knowledge of their environment tend to have more complex mental maps and are more likely to think in terms of cardinal directions (Shelton and McNamara, 2004). Forty-eight participants (44 percent) agreed or strongly agreed they were "very good at reading maps" but just 18 agreed or strongly agreed they "enjoy reading maps." Table 17 summarizes the overall descriptive statistics by item for the spatial survey.

Table 17. Summary of spatial survey results (n=109)

	SA	1	2	3	4	5	6	SD	Mean	Mean (reverse scale)	Std
1. I am very good at giving directions.		4	36	33	22	11	3		**3.08**	**3.92**	1.16
2. I have a poor memory for where I left things.		4	19	24	16	39	7		3.81		1.36
3. I am very good at judging distances.		8	29	32	22	14	4		**3.16**	**3.84**	1.26
4. My "sense of direction" is very good.		13	29	32	18	13	4		**3.01**	**3.99**	1.32
5. I tend to think of my environment in terms of cardinal directions (N, S, E, W).		4	8	16	16	29	36		**3.93**	**2.48**	1.45
6. I very easily get lost in a new city.		11	21	20	26	26	5		3.46		1.42
7. I enjoy reading maps.		3	15	26	24	22	19		**3.95**	**3.05**	1.40
8. I have trouble understanding directions.		2	5	14	21	49	18		4.50		1.16
9. I am very good at reading maps.		15	33	30	23	7	1		**2.79**	**4.21**	1.17
10. I do not remember routes very well while riding as a passenger in a car.		6	13	10	22	33	25		4.27		1.50
11. I do not enjoy giving directions.		17	20	25	27	17	3		3.15		1.39
12. It is not important to me to know where I am.		2	4	7	15	25	56		5.06		1.24
13. I usually let someone else do the navigational planning for long trips		28	21	24	23	11	2		2.76		1.40
14. I can usually remember a new route after I have traveled it only once.		14	30	28	16	15	6		**3.06**	**3.94**	1.41
15. I do not have a very good "mental map" of my environment.		1	2	18	22	39	27		4.62		1.14
16. I do not confuse left and right much.		55	27	8	7	4	8		**2.10**	**4.90**	1.53
17. I tend to think visually, with lots of mental images.		54	35	12	7	1	0		**1.77**	**5.23**	0.95

Notes: Items in bold text indicate a reversed scale was used to calculate the spatial survey scale.
SA = strongly agree. SD = strongly disagree

Responses to the spatial survey indicate a difference between what the participants believed their skills and aptitudes to be and what they actually practiced in life. *Reciprocal determinism*, a central premise of Bandura's (1978) social cognitive theory, proposes that high self-efficacy for a subject or skill may translate to higher or better performance. Likewise, low self-efficacy may translate to lower performance influenced by low self-belief. Studies of the relationship between self-efficacy and performance tend to draw on the theory of reciprocal determinism. However, this postulated positive correlation is sometimes presumed without strong empirical support (Williams and Williams 2010). Results of the spatial survey were analyzed further in order to explore potential relationships between self-efficacy and performance.

Development of the Spatial Survey Scale and Categories

Quantitative comparison of item responses, using principal component analysis (PCA), allows statistical identification of underlying components, or factors, in the spatial survey. Combined, the 17 items displayed an acceptable level of internal reliability ($\alpha = 0.78$). In the initial run of the PCA, the Kaiser-Meyer-Olkin (KMO) values for all 17 items were acceptable (> 0.60). Communalities, however, for items 5 and 16 had unacceptably low values (below 0.50), and were therefore removed for the second iteration. In the second iteration, KMO values were acceptable and Bartlett’s test was significant. Communalities for the remaining 15 items were acceptable (>0.50). The second iteration yielded 4 well-delineated components, except for item 17 which demonstrated complex structure weighted equally between two components. The total explained variance, however, was unacceptable at 54.89 percent (threshold is 60 percent), and therefore item 17 was removed for a third iteration of the PCA. In the third iteration, item 6 had an unacceptably low communality value (0.367) and was subsequently removed. In the fourth and final iteration, the remaining 13 items had acceptable KMO values, communalities, and Bartlett's test was significant. This yielded four components explaining 60.4 percent of the variance. Item 1 was a complex item loading equally on component 1 and 2 (Table 18).

Table 18. Factor analysis loadings of the spatial survey items.

Rotated Component Matrix

	Component			
	1	2	3	4
10	0.781			
14	0.759			
3	0.676			
4	0.623			
15	0.608			
12	0.478			
11		0.771		
13		0.739		
1	0.547	0.582		
9			0.755	
7			0.751	
2				0.749
8				0.715

Extraction Method: Principal Component Analysis.
Rotation Method: Varimax with Kaiser Normalization.
Items 5, 6, 16, & 17 were removed from the factor analysis.

Internal reliability was assessed for the four components using Cronbach's alpha. Components 1 and 2 had acceptable alpha levels. All 17 items combined, as one component, had a higher level of internal reliability than components 3 and 4 separately (Table 19).

Table 19. Summary of components in the spatial survey.

Factor	Title	Items	α
Component 1	"Location, distance, direction"	1, 3, 4, 10, 12, 14, & 15	0.81
Component 2	"Navigation"	1, 11, & 13	0.61
Component 3	"Map reading"	7 & 9	0.51
Component 4	"Spatial memory"	2 & 8	0.40

A sum scale for the spatial survey was calculated by adding the scores for all 17 items. Scores for positively stated items were reversed so that high values indicated a high level of self-efficacy for spatial habits and skills and low values indicated low levels of self-efficacy. The scale was normalized by dividing the total by the possible range thus converting the scale to a percent scale with a minimum value of zero and a maximum of 100. For comparison and correlation, a scale was created for each of the four components by taking the sum of points for each item represented in the component, subtracting the minimum possible value, and dividing the sum by the range of the scale. The equation used for component 2 is provided as an example of the method used to calculate the scales:

$$[((\text{Item 1 score} + \text{Item 11 score} + \text{Item 13 score}) - 3) / 15 * 100$$
$$= \text{Component 2 scale (percent)}]$$

Assumptions of normal distribution for the sum scales of component 1 and 2 were explored with descriptive statistics. The sum scale for the spatial survey had a distribution close to normal with the mean equal to the median (60 percent) and with no skew.

Correlations were also explored between the sum scale and component 1, "location, distance, direction." The two scales had a large positive and statistically significant correlation ($r = 0.872$). The correlation between the sum scale and component 2, "navigation", was also positive and significant ($r = 0.692$), but not as large as the relationship between the sum scale and component 1.

Component 1 had the strongest internal reliability and was strongly correlated with the overall sum spatial survey scale. However, because the distribution of scores in the overall sum scale were closer to a normal distribution, lacked a skew in either direction, the mean was similar to the median (60 percent), and the sum scale had the smallest variance (out of the sum, component 1, and component 2); the overall sum scale was used to define spatial survey categories based on self-reported survey data and to explore correlations between self-efficacy and spatial skill, and self-efficacy and spatial relations content knowledge. Table 20 summarizes the descriptive statistics for the sum scale, component 1, and component 2.

Table 20. Descriptive statistics for the spatial survey sum scale, component 1, and component 2

	Mean (%)	Median (%)	Std	Skewness	Min	Max
Sum Scale	59.05	60.00	12.28	-0.04	28.00	93.00
Component 1	64.72	68.57	17.57	-0.60	17.14	97.14
Component 2	45.50	46.67	19.79	-0.01	0.00	100.00

Using a histogram and frequency table of the spatial survey sum scale, three categories were created and labeled low spatial survey, average spatial survey, and high spatial survey. The categories were determined by spacing the numerical breaks an equal distance from the rounded mean of 60.0 percent. The low break was placed at 55.0 percent and a high break at 65.0 percent providing a span of 10 percentage points between the two breaks with the mean falling at the midpoint of the interval.

The breakdown of participants after they were grouped into category by spatial survey provided a relatively equal distribution of participants in the three categories: low (n = 36), average (n = 37), and high (n = 36). The distribution of males and females in the spatial survey categories, however, fell into an unequal pattern. More males than females were in the high spatial survey category (n = 23 and n = 13, respectively), and more females than males were in the low spatial survey category (n = 23 and n = 13, respectively). Relatively equal numbers of males and females fell in the average spatial survey category. Chi-square analysis indicates no statistically significant difference for the count of males and females in the three spatial survey categories ($x^2 = 0.062$). Comparison of the number of males and females by spatial survey category are summarized in Figure 21.

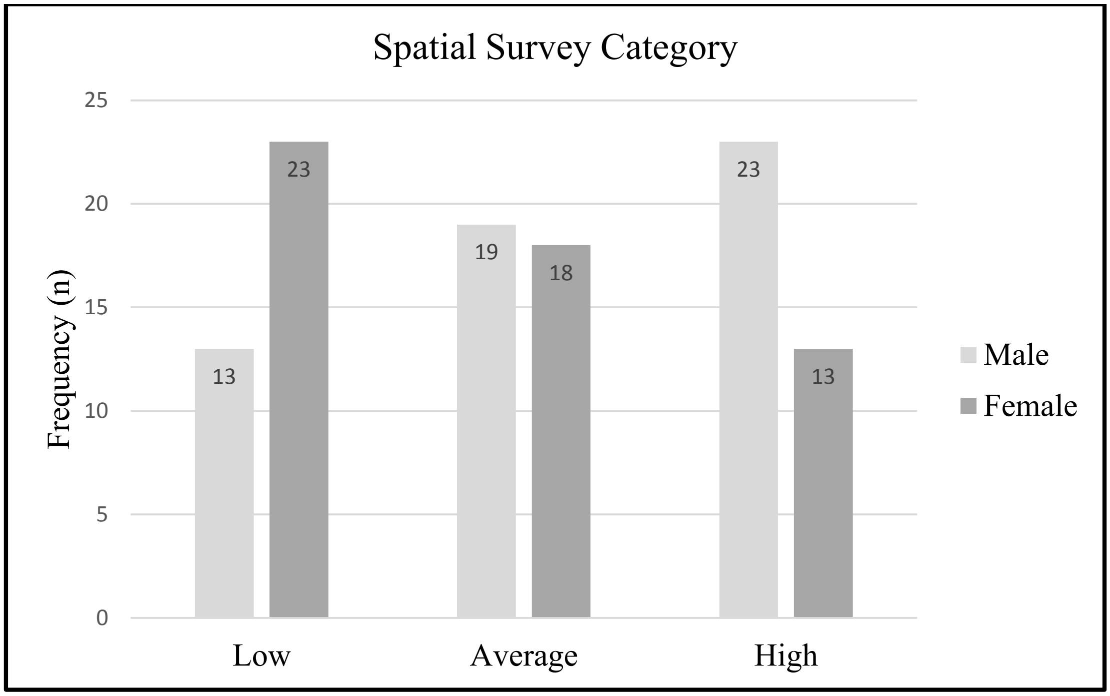


Figure 21. Summary of males and females by spatial survey category

Relationships Between Self-Efficacy and Spatial Skills

According to the theory of reciprocal determinism, one would expect to see a positive linear relationship between self-reported levels of self-efficacy for spatial habits and attitudes and levels of spatial skills and between spatial survey results and spatial relations content knowledge. Utilizing the sum average of pretest scores for spatial skills, the post spatial relations scores (less the task-based items), gains on the spatial relations content test, and the spatial survey sum scale; this relationship was explored with scatterplot graphs and Pearson correlations. The results contradicted the expectation based on reciprocal determinism. When comparing the participants, no relationship between the spatial survey and spatial skills ($r = 0.099$), between the spatial survey and post spatial relations content knowledge (r = -0.003), nor between the spatial survey and gains to spatial relations content knowledge (r = -0.012) was evident (Table 21, Figure 22).

Table 21. Pearson correlations among spatial survey, spatial skills, and content knowledge

Correlations

		Pre spatial skills average	Post spatial relations content	Spatial relations content change (post % - pre %)
spatial survey sum scale	Pearson Correlation	0.099	-0.003	-0.012
	Sig. (2-tailed)	0.304	0.979	0.916
	n	109	82	82

Note: Correlations for spatial relations content exclude individuals in the control group.

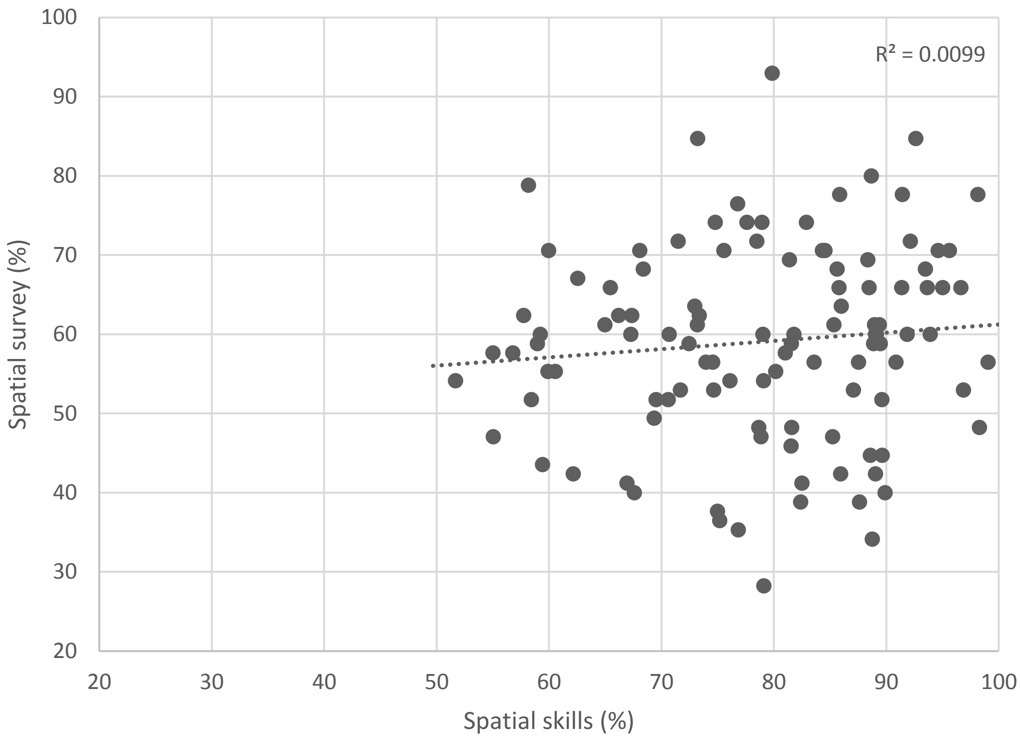


Figure 22. Scatterplot graph comparing spatial skills and spatial survey results (n=109).

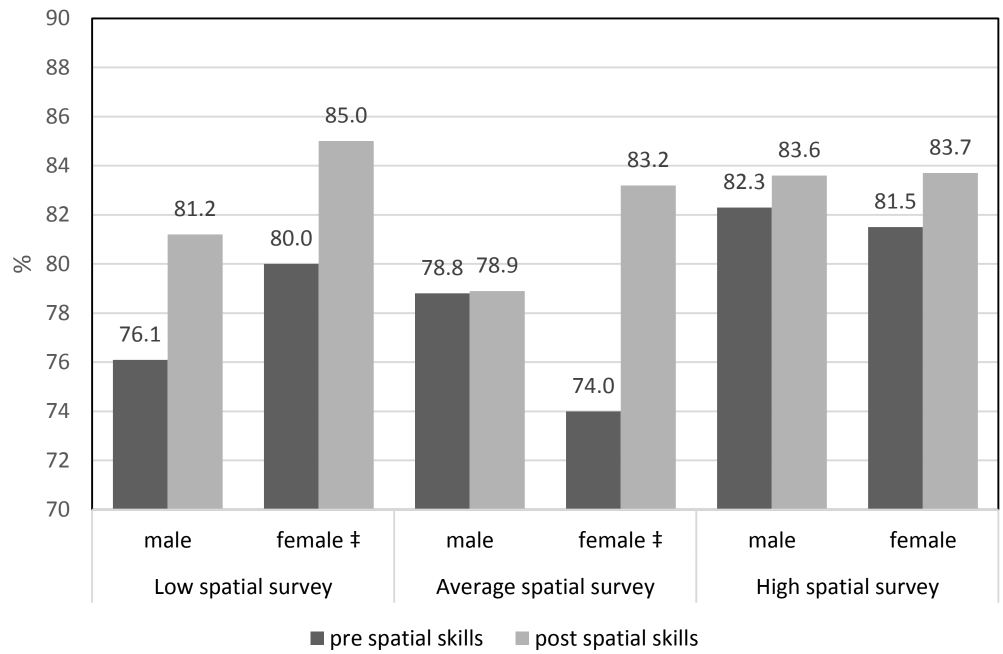
Influence of Spatial Survey Category on Spatial Skills

Pre spatial skills and post spatial skills (based on average accuracy scores) were compared for the three spatial survey categories (low, average, and high) using analysis of variance. No difference between pre and post spatial skills existed for any of the three spatial survey groups. A paired T test was calculated for pretest and posttest spatial skill scores to determine if a difference existed for the three spatial survey groups. Significant gains were found pre to post for the low (p=0.008) and the average spatial survey group

(p=0.012). The high spatial survey group had a small positive, but insignificant, gain (p=0.312).

The spatial survey categories were further divided by sex to explore the influence of sex and self-reported spatial attitudes on changes to spatial skills. An analysis of variance was used to identify differences in the six groups: male or female; and low, average, or high spatial survey group. No difference existed in the six groups for pre spatial skills or post spatial skills. No sex difference was present on pretest scores or on posttest scores. When comparing gains pretest to posttest, however, low and average spatial survey females had statistically significant gains pre to post in spatial skills (p=0.031 and 0.000, respectively). All three male groups had small positive, but insignificant, gains.

Results suggest that females have a tendency to underestimate their spatial skills whereas males tend to overestimate their skills. Prior research has explored sex differences in individuals' performance expectancies and self-efficacy. Although there are exceptions, females are typically less self-confident and less likely to attribute success to ability, particularly on stereotypical masculine tasks (Schunk and Lilly 1984). In addition, the significant gains pretest to posttest in spatial skills for females that ranked themselves lower in the spatial survey indicate that practice and training may have a positive effect on spatial skills for females. Figure 23 illustrates the changes in combined average spatial skills pre to post for males and females in the three spatial survey groups.



ǂ Statistically significant positive difference at the 0.05 level between the pretest and the posttest mean scores.

Figure 23. Changes in spatial skill average scores by spatial survey category and by sex

A crosstabulation between spatial skill categories versus spatial survey categories was performed to compare the number of males and females per cell. Even though there is no relationship between spatial skill scores and spatial survey scores by individual, a crosstabulation assists in identifying trends by category. A chi-square analysis indicates no statistical difference in cell numbers between spatial skill and spatial survey categories for males or females (x^2= 0.276 and 0.308, respectively). Nevertheless, males who rated themselves high on the survey were most likely to score high on the spatial skills pretest (n=11). High spatial skill females, on the other hand, were most likely to self-rank in the lower third on the spatial survey. Males that scored in the low spatial skill group, were equally likely to rank as low, average, or high in the spatial survey. Females that scored in the low spatial skill category were more likely to score themselves as low or average spatial thinkers in the spatial survey. Table 22 summarizes the crosstabulation results. For this sample, results indicate males were somewhat more accurate in their self-assessment than the females regarding spatial skills, especially for the high spatial skill category.

Table 22. Crosstabulation

Crosstabulation: Spatial Survey Category by Spatial Skill Category					
			Spatial Skill Category		
			Low	Average	High
Male	Spatial Survey Category	Low	7	4	2
		Average	5	7	7
		High	6	6	**11**
Female	Spatial Survey Category	Low	7	8	**8**
		Average	9	5	4
		High	2	7	4

Influence of Spatial Survey Category on Spatial Relations Content Knowledge

Spatial relations content knowledge scores were compared for the three spatial survey categories using analysis of variance. The control group was excluded from analysis in this step because they did not receive any instruction about spatial thinking strategies or central place theory. No difference existed for any of the three spatial survey groups for content-dependent, content-independent, or overall scores in either the pretest or the posttest. A paired T test was used to determine if a difference in gains from pretest scores to posttest scores was present for the three survey groups. Significant gains were present for the low ($p=0.04$) and the average spatial survey group ($p=0.01$) for content-independent knowledge. Although not significant, the high spatial survey group did have moderate gains in the content-dependent item category (11.9 percent, $d=0.58$).

The spatial survey categories were further divided by sex to explore the influence of sex and self-reported spatial attitudes on spatial relations content knowledge. An analysis of variance was used to identify differences in the six groups. No difference was found in the six groups for pretest scores or posttest scores. When comparing pretest to posttest gains, average spatial survey females had statistically significant gains on the content-dependent item category ($p=0.023$). Moderate gains were evident in several other groups, but large standard deviations rendered the gains statistically insignificant. No clear pattern of a sex related advantage was evident.

Finally, spatial survey categories were further divided into instructional groups (intervention or comparison) to explore the interaction of instructional delivery, self-attitudes, and sex with regard to spatial relations content knowledge. An analysis of variance was used to identify differences in the 12 subgroups. No difference was found for pre or post content knowledge scores. When comparing gains pretest to posttest, however, the average spatial survey females in the intervention group (n=6) drove the statistically significant gains in the content-dependent item category (p=0.009, 29.4 percent gain). No pattern of advantage for spatial relations content knowledge is evident based on spatial survey category. In other words, self-efficacy appears to have little to no bearing on spatial relations content knowledge.

Choice of instructional method does appear to influence spatial relations content knowledge for the average and high spatial survey subgroups. Although the means are not significantly different, a slight advantage to the digital method of instruction is apparent for the content-dependent item category. With the exception of the low spatial survey males, the intervention groups made greater mean gains in their content-dependent scores than the paired comparison groups. Figure 24 and Figure 25 illustrate the means and confidence intervals for the twelve groups' content-independent scores and content-dependent scores. The lack of discernable pattern in scores for the groups and large variations are evident in the figures.

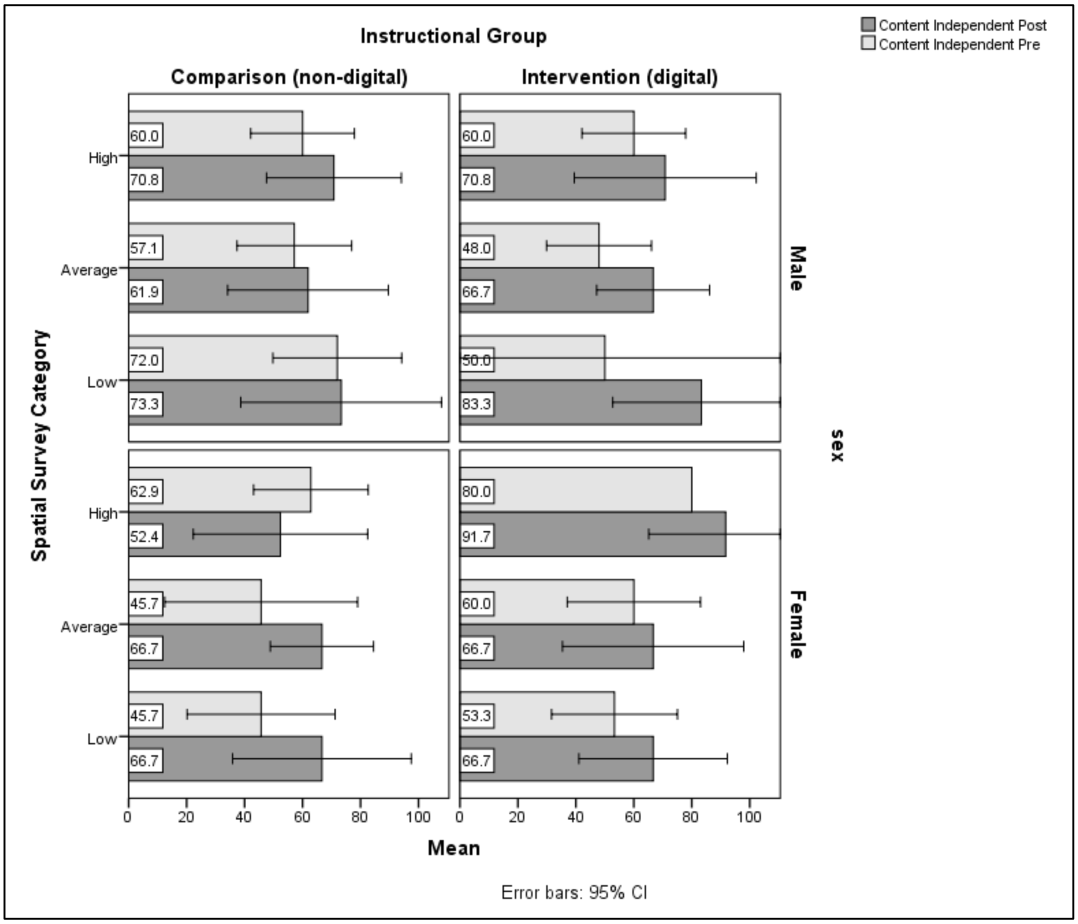


Figure 24. Clustered bar graphs with error bars (95 percent confidence intervals) for the spatial relations content-independent item category.

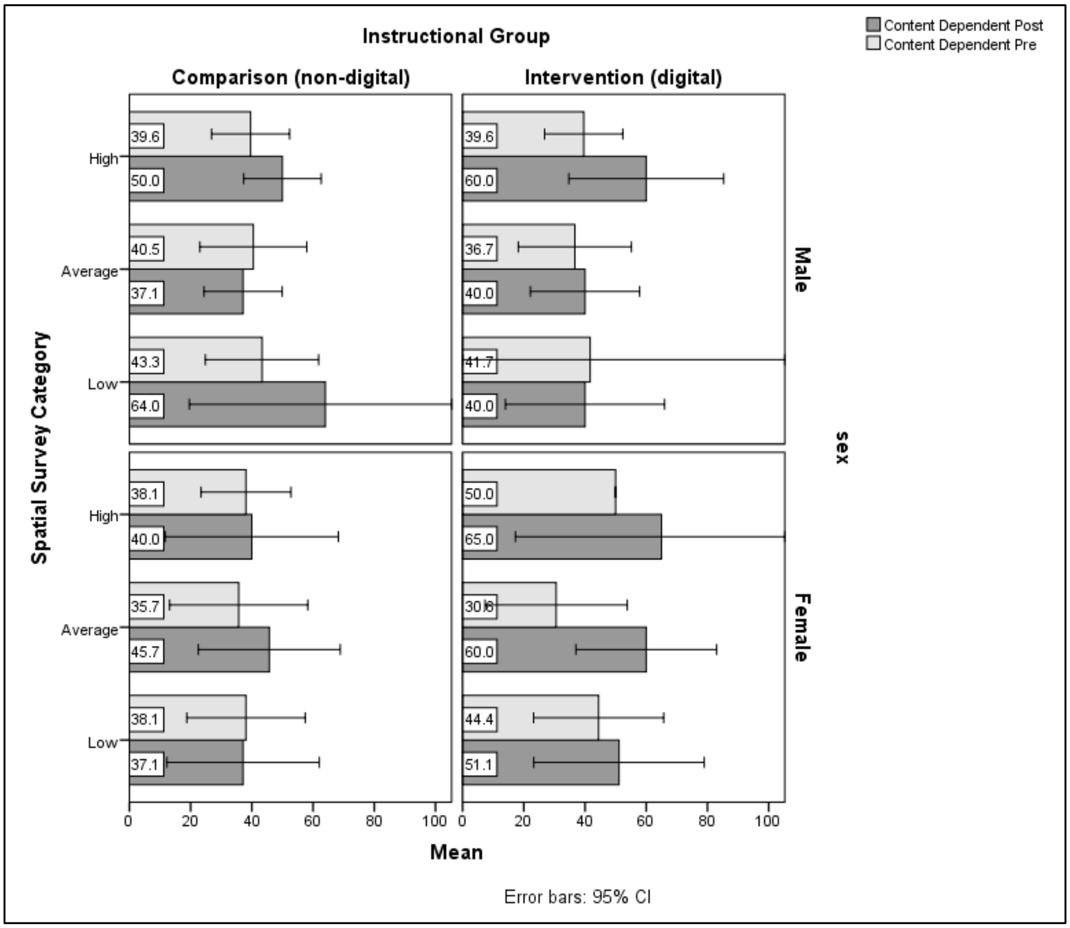


Figure 25. Clustered bar graphs with error bars (95 percent confidence intervals) for the spatial relations content-dependent item category.

SUMMARY

A brief summary of the results is addressed in this section in the same sequence the three research questions were posed. The first question asked, what is the effect of using GST as an instructional tool on students' spatial thinking skills? Spatial skills were assessed with a battery of three tests intended to measure 2-dimensional spatial visualization, 3-dimensional spatial visualization, and spatial orientation. Pretest results were compared to posttest results for three treatment groups: control, comparison, and intervention. The control group received no instruction about spatial thinking strategies or central place theory. The comparison groups received instruction about spatial thinking skills and central place theory using traditional paper-and-pencil maps as the visualization tool. The intervention group received instruction using GST. If the instructional method had an impact on students' spatial skills, a difference between the control group and the instructional groups would be present. It was not. In this case, the control group gained in spatial skill accuracy roughly as much as the other two groups. Using GST had no effect on students' spatial skills. Practice and retesting of spatial skills, however, did have a positive impact. All groups gained in 2-D and 3-D spatial visualization skills. Spatial orientation skills appear to be less malleable in that very little change was evident pretest to posttest for all groups.

The second question asked, what is the effect of using GST as an instructional tool on students' content knowledge of a spatial concept in geography? Spatial relations content knowledge was measured with an instrument developed by the researcher for this project. Items from the test were classified as content-independent, items that could be answered using primarily spatial skills, and content-dependent, items that required knowledge of central place theory in addition to spatial skills. A third category of test items, task-based items, was not considered in the analysis.

Positive gains in content knowledge were evident in both treatment groups compared to the control group. Only the intervention group, however, demonstrated significant gains pre to post in both content-dependent and independent item categories. These results support the hypothesis that using GST for teaching and learning has a greater positive effect on students' content knowledge of a spatial concept in geography than using another approach.

The last question asked, what is the relationship among spatial thinking skills, self-attitudes towards spatial and navigational abilities, and change in students' content knowledge of a spatial concept in geography? This question contains several sub-questions. First, does an individual's starting spatial skill level influence change (gain or loss) to his or her spatial skills? Participants' starting spatial skill level, as determined from pretest scores, were used to divide the sample into three spatial skill categories: low, average, and high. The categories were then used to compare posttest spatial skill scores and change pre to post. The low spatial skill group had the largest gains pre to post for 2-D and 3-D visualization skills. The average spatial skill group also had statistically significant gains pre to post for 2-D and 3-D visualization skills. None of the three groups evidenced improvement in spatial orientation. The high spatial group made very little, if any, gains in accuracy on any of the three spatial skills tests. A ceiling effect may have limited their gains. Based on these results, starting spatial skill level does influence change to spatial skills. The low spatial skill group had much more room for gain, and through the practice provided by testing and retesting, improved their spatial skills significantly.

Second, does an individual's starting spatial skill level influence change to his or her spatial relations content knowledge? All three spatial skill groups gained in the content-independent item category, as measured by the spatial relations content test. Only the high spatial skill group, however, demonstrated significant gains. In the content-dependent item category, no change was evident for the low and only a small gain was made by the average spatial skill participants. The high spatial group, however, demonstrated significant gains for both content-independent and dependent scores.

This phenomenon was analyzed further by dividing the spatial skill groups into instructional groups. This analysis revealed that not only was the high spatial skill group outperforming the low and average, but the intervention high spatial skill group was outperforming its counterpart. An additional layer of analysis was explored by dividing these subgroups by sex. In general, high spatial skill males and females accounted for the significant content knowledge gains in the intervention group. High spatial skill individuals consistently outperformed low and average individuals, and the advantage was larger in the GST than in the comparison group. Trends in the low and average spatial skill groups indicate large variations due to sex and instructional method. No clear pattern of male or female advantage was present in the low or average spatial skill groups. Likewise, no clear pattern of advantage due to method of instruction was evident for the low and average spatial skill groups. These results suggest that an individual's starting spatial skill level does influence change to spatial relations content knowledge especially for high spatial skill individuals using GST.

Third, does a relationship exist between self-attitudes towards spatial and navigational abilities for spatial tasks and spatial skills? The Santa Barbara Sense of Direction survey was modified and administered for this study to measure individuals' self-efficacy for spatial tasks. Results of the 17-item survey were summed and normalized, and a spatial survey scale was developed to quantify self-efficacy. A scatterplot graph and correlation analysis demonstrated that a relationship between spatial survey scores and spatial skill scores does not exist.

Using a method similar to that for defining spatial skill levels, the spatial survey scores were used to define low, average, and high spatial survey groups. The spatial survey categories were then subdivided by sex to explore whether a relationship with spatial skills existed. It has been established that instructional method had no impact on spatial skills and was, therefore, not considered as a factor for this step.

Significant gains in spatial skills were present pre to post for the low and the average spatial survey group. The high spatial survey group had a small positive, but non-significant, gain. Sex differences were evident. Low and average spatial survey females had statistically significant gains pre to post in spatial skills. All male groups had small, insignificant, positive gains. These results suggest that females have a tendency to underestimate their spatial skills. It also suggests the positive effect practice and training may have on underlying spatial skills especially for females.

Finally, does a relationship exist between self-attitudes about spatial and navigational abilities and spatial relations content knowledge? This possibility was explored with a scatterplot graph and correlation analysis. No relationship was evident. The spatial survey categories were divided by instructional group, and then again by sex to explore the interaction of instructional delivery, self-attitudes, and sex with respect to spatial relations content knowledge. An analysis of variance was used to identify differences in the 12 groups: male or female; low, average, or high spatial survey group; and intervention or control group. No difference was found in the 12 groups for pre content knowledge scores or post content knowledge scores. No sex difference in the pretest or posttest scores was detected between the instructional groups. When comparing gains pretest to posttest, the average spatial survey females in the intervention group (n=6) drove a statistically significant gain in the content-dependent category items. Comparing gains for the subgroups, no pattern based on spatial survey category is evident. In other words, self-efficacy ratings appear to have little to no bearing on spatial relations content knowledge.

Instructional method does appear to influence spatial relations content knowledge for the average and high spatial survey groups. A slight advantage to using GST is demonstrated in the higher scores for the post content-dependent category items. With the exception of the low spatial survey males, the intervention groups made greater mean gains in their content-dependent scores than the comparison groups.

A small positive relationship does exist between self-attitudes towards spatial and navigational abilities for spatial tasks, spatial skills, and content knowledge although the relationship is complex and non-linear. Sex influences how individuals perceive their own abilities, and sex combined with self-efficacy is related to spatial skills and content knowledge. In general, females tend to score themselves lower, but those who rated themselves low or average, were more likely to have greater gains in spatial skills.

In the next chapter, conclusions will be provided. The results will be interpreted and explained in the context of previous research findings. The design of the study will be analyzed and the strengths, limitations, and recommended changes will be discussed. Finally, recommendations for K-12 education will be made based on the results of the study.

CHAPTER V

DISCUSSION AND CONCLUSIONS

This study examined the influence of instruction of a spatial concept with GST on spatial skills and content knowledge. It also explored interactions among spatial skills, sex, self-attitudes towards spatial and navigational abilities, and spatial relations content knowledge. A quasi-experimental design was utilized to compare an intervention, a comparison, and a control group. The intervention group completed a central place unit of study using GST as a geovisualization tool. The comparison group also received instruction about central place theory but utilized paper maps rather than GST. Both the intervention and comparison groups received instruction concerning spatial thinking strategies. The control group received neither central place theory nor spatial thinking strategy instruction. Changes to students' spatial skills and content knowledge were measured pre to post using an array of tests: 2-D and 3-D spatial visualization, spatial orientation, and spatial relations content knowledge. Students' self-reported attitudes towards spatial and navigational abilities were measured with a questionnaire administered prior to intervention. This chapter discusses conclusions of the study and interprets and explains the results in context of previous research findings. The chapter also discusses the implications applications of the results and closes with recommendations for future research and policy. Discussion begins with interpretation of the data followed by implications of the results, then recommendations.

INTERPRETATION OF THE RESULTS

It is generally thought the use of GST enhances students' spatial thinking and that it is an ideal tool for teaching spatially dependent concepts. This study is one of the first attempts to demonstrate an association between instruction using GST and changes to spatial skills and/or spatially dependent content knowledge. High spatial ability is positively correlated with success in geography and other sciences. Spatial skills are malleable and improve with training and practice. Theoretically, then, a gain in spatial skills obtained through training and practice should be associated with greater success in learning a spatially dependent concept. Participants in this study received explicit instruction in spatial thinking strategies while using GST to study central place theory, a spatially dependent geography concept. The impact of GST on spatial skills and content knowledge is described in the following sections.

EFFECT OF GST ON SPATIAL SKILLS

Many have proposed using GST to improve spatial skills and assert that using GST improves students' spatial thinking (Committee on Support for Thinking Spatially 2006). Results of this study, however, do not support this assertion. The control, comparison, and intervention group demonstrated equal and moderate gains in accuracy pre to post in spatial visualization skills (2-D and 3-D). The gains were statistically significant at a 0.05 level for all groups for the 2-D spatial visualization and for the intervention group for the 3-D visualization. In contrast, the groups demonstrated no change pre to post in accuracy for spatial orientation skills. All groups became more efficient at orientation—they completed more items in the post than in the pre—but with no gains in accuracy.

These findings suggest that spatial orientation skills are more resistant or less malleable than spatial visualization skills. This is consistent with prior work (Piburn et al. 2005). It is also consistent with research that has found little, if any, differences in subjects' performances for the water-level task and the rod-and-frame test, regardless of training or instruction (Robert and Ohlman 1994; Vasta and Liben 1996). Both tasks require the individual to identify horizontal and vertical orientations while ignoring a frame or container. It is not known what type of spatial skill is utilized for tasks such as the water level task or if there is a correlation between performance on the Object Perspective Test (Hegarty and Waller 2004), used in this study to measure spatial orientation, and performance on the water level task. It is evident from prior work, however, that some spatial tasks are resistant to change. The results of this study suggest spatial orientation, as measured by the Object Perspective Test, may be such a skill.

The relatively equal accuracy scores for the three groups also implies that gains pre to post were most likely due to a test-retest effect and were not affected by the instructional unit or by the use of maps, digital or paper. Using GST had no effect on students' spatial skills. Practice and retesting of spatial skills, however, did have a positive impact. All groups gained in 2-D and 3-D spatial visualization skills. These findings suggest that spatial visualization skills are malleable, consistent with previous research (Terlecki 2004; Wright et al. 2008). Spatial visualization skills can improve significantly with practice and training in the specific skill.

Spatial visualization tests, such as the Vandenberg test, consistently yield differences in performance between males and females (Freedman and Rovegno 1981; Linn and Peterson 1986). Results from this study do not support a sex advantage. Male and female pretest and posttest scores were compared using an independent samples *T* test. No statistical differences were found. Mean scores on all measures of spatial skill were essentially equal for male and female participants.

Researchers have argued that use of GST can change the way mental images are formed, stored, and utilized (Uttal 2000) and that use of technology to create external visualizations can compensate for an inability to visualize structures and patterns mentally (Hegarty et al. 2007), thus enhancing spatial thinking. This study's findings do not support these previous results, perhaps because of the brevity of the instructional treatment. A more lengthy use of GST could enhance spatial skills.

EFFECT OF GST ON SPATIAL RELATIONS CONTENT KNOWLEDGE

Changes to participants' spatial relations content knowledge was measured with a content test developed specifically for this project and related to the topic of central place theory. The test consisted of three types of items: content-independent, requiring primarily spatial skills to answer; content-dependent, requiring knowledge about central place theory; and task-based items. All three question categories measured spatial thinking as defined in *Learning to Think Spatially* (2006): concepts of space, tools of representation, and higher level processes of reasoning. Results of the content tests were analyzed by comparing scores of the three instructional groups.

A significant difference between the two treatment groups and the control group was evident for the content-dependent and independent item categories. No significant difference was found for the task-based items; each instructional group had substantially lower scores pre to post on the task-based items. No significant differences existed between the two treatment groups in pretest scores or posttest scores for any category on the spatial relations content test. Even though both treatment groups saw gains pre to post in their content knowledge, only the intervention group had statistically significant gains, a 15.0 percent ($p = 0.01$) increase in content-independent and a 11.9 percent ($p = 0.05$) increase in content-dependent items.

These findings suggest that, first, the content-dependent items were more difficult than the content-independent items. Both groups' scores improved more for content-independent items. Both types of questions required spatial skills to answer; the content-dependent items also required understanding central place theory. In other words, as their description implies, content-independent items did not require an understanding of the content.

Second, the control group's scores decreased for both item categories, significantly for the content-dependent items (27 percent). This finding aligns with prior research highlighting the difficulty in transferring a general skill to a specific content domain (Devon, Engel, and Turner 1998; Fong and Nisbett 1991). The control group had similar gains in spatial skills as the treatment groups, yet this skill did not transfer to achievement on the content-independent item category. Because the control group's scores decreased for the content-independent item category and the treatment group's did not, suggests the treatment groups' spatial skills may have improved more than the control's from spatial thinking instruction.

Third, even though both treatment groups had gains in content knowledge, only the intervention group demonstrated significant gains pre to post. This suggests that using GST for teaching and learning had a greater positive effect on students' spatial relations content knowledge than using a more conventional technique.

SPATIAL SKILL CATEGORIES AND CHANGES IN SPATIAL SKILLS

Participants were categorized as low spatial, average spatial, and high spatial based on their pretest scores. Analysis of variance was used to explore the influence of initial spatial skill level on pre to posttest changes in spatial skills. Several interesting relationships emerged. First, the high, average, and low groups consistently demonstrated high, average, and low mean scores on the pretests for all three of the spatial skills measured: 2-D spatial visualization, 3-D spatial visualization, and spatial orientation. Second, using an independent sample T test, a statistically significant difference was present for all three groups' pretest scores for 2-D and 3-D visualization, and a significant difference between the high spatial group and the other two groups for orientation skills. Third, even though the low spatial group had the greatest gains, their posttest scores remained significantly lower than the other groups' for 2-D and 3-D visualization (p=0.00). On the other hand, although the high spatial group's orientation scores decreased, their posttest scores remained significantly higher than the other groups' scores. A gap remained, between the high and low skill groups' mean scores, but the gap narrowed noticeably. Both the low and average spatial groups' 2-D and 3-D visualization scores improved significantly.

These results suggest that individuals with low (or high) spatial visualization scores also tend to have low (or high) spatial orientation scores. This does not support the findings of previous research (Hegarty and Waller 2004; Zachs et al. 1999) that have indicated visualization and orientation are separate, independent skills. This study found weak, but significant, positive correlations for subjects' scores on the three spatial skill tests.

Individuals in the high spatial skill group showed no gains pre to posttest. This was likely due to a ceiling effect as they scored near the maximum value on the pretests. The low spatial skill group, on the other hand, had the greatest potential to improve their scores. In education research, it is not uncommon for results to exhibit a ceiling effect, especially when trying to measure skills or knowledge of a gifted population. Standard statistical methods, such as analysis of variance or comparison of means, can produce biased estimates when a ceiling effect is present (McBee 2010). Therefore, it is feasible that participants in the high spatial group improved their spatial skills, but the instrument's limited range did not capture it. Prior research supports the trend, identified here, of the lowest skill-level group demonstrating the largest gains from training of spatial skills. Studies exploring the effects of training on spatial thinking strategies have found that training especially benefits individuals with lower spatial ability (Gyselinick et al. 2009; Meneghetti et al. 2013). Prior research also supports the finding here that, even with large gains for the lowest skill-level, the significant gap between low-skill and high-skill will narrow but still persists after training (Miller and Halpern 2012; Sorby 2009).

SPATIAL SKILL CATEGORIES AND CHANGES IN SPATIAL RELATIONS CONTENT KNOWLEDGE

The influence of starting spatial skill level on changes to spatial relations content knowledge was explored with analysis of variance using the spatial skill categories as the grouping variable. Only content-independent items and content-dependent items were included for this analysis. Task-based items were not included for reasons discussed previously, namely that the control group demonstrated no gains in content knowledge.

Pretest scores did not differ among the groups. Posttest scores did not differ among the groups for the content-independent item category, but the high spatial skill group scored significantly higher than the other two groups for the content-dependent item category.

Pre to posttest scores improved for all spatial skill groups. The low spatial skill group improved 8.5 percent in the content-independent item category and 0.1 percent in the content-dependent item category. The average spatial skill group improved 10.8 percent in the content-independent item category and 5.1 percent in the content-dependent item category. The high spatial skill group improved 15.4 percent pre to posttest in the content-independent item category and 23.1 percent in the content-dependent item category. Only the gains of the high spatial skill group were statistically significant.

Results suggest participants with a high level of spatial skill, without consideration to instructional method, are more successful at acquiring spatial relations content knowledge. Prior research supports the finding that high spatial skills can predict academic success in the sciences, especially spatially dependent sciences such as geography, geology, and engineering (Ormand et al. 2014).

The low and average spatial skill groups gained more in the content-independent item category, whereas the high spatial skill group gained more in the content-dependent item category. This implies a higher level of transfer by the high spatial skill group of spatial skills to a discipline-specific topic. In this example, without consideration to the instructional method, individuals with high spatial skill prior to intervention gained a better understanding of central place theory. Evidence of transfer from training in spatial skills to an improved ability to understand and solve discipline-specific spatial problems is scarce (for an exception see Talley 1973). These results, however, imply more successful transfer by the high spatial skill group.

Instructional Group

Thus far, results support the premise that teaching spatially dependent concepts (e.g., central place theory) using GST increases spatial relations content knowledge more than teaching them with a traditional, paper-and-pencil method. In addition, results indicate that individuals possessing high spatial skill acquire content knowledge better and/or faster than low or average spatial skill individuals. The interaction between individuals' spatial skill level and instructional method, and the impact that interaction may have on spatial relations content knowledge was explored by dividing the spatial skill groups by instructional group: comparison and intervention.

The low spatial skill group demonstrated small change in content knowledge regardless of the instructional group. Scores were slightly higher in the intervention group, but the difference in scores between instructional groups was insignificant. Based on these results, instruction with GST made no difference to content knowledge for the low spatial group.

The average spatial skill group seemed to perform better in the comparison group with medium, albeit insignificant, increases in scores for both content-independent and content-dependent item categories (13.9 percent, d=0.66; 12.7 percent, d=0.62, respectively). The average spatial intervention group demonstrated little to no change in content knowledge. These results infer that individuals of average spatial skill level may learn spatially dependent content more effectively in a traditional paper-and-pencil format. Generalizations, however, cannot be made in this case due to the small unequal sample sizes, insignificant differences between instructional groups, and the large variation for the groups.

The high spatial skill group clearly performed better in the intervention group with large and significant increases in scores for both item categories. For the content-independent item category, the high spatial skill intervention group improved by 28.1

percent compared to 5.4 percent in the comparison group. In a similar pattern, for the content-dependent item category, the high spatial skill intervention group improved by 35.4 percent compared to a 13.5 percent gain by their comparison. Overall, when comparing participant groups by both spatial skill level and instructional method, the high spatial individuals in the instructional group utilizing GST had the most substantial gains in spatial relations content knowledge.

The use of GST, in this case, had no differing effect on the low spatial skill group, a negative effect on the average spatial skill group, and a large positive effect on the high spatial skill group. The opposing patterns may be explained by differences in strategy selection, cognitive overload, or a combination of both. Prior findings suggest that spatial thinking and success in solving spatial tasks varies in individuals not only because of differences in spatial skills, but also differences in strategic approaches and the complexity or difficulty of the spatial task (Gluck and Fitting 2003; Kyllonen, Lohman, and Snow 1984). “The best performers may be those who have a large repertoire of strategies and are able to select the best strategy based on characteristics of each task” (Gluck and Fitting 2003, 302). A link between visual strategy selection and performance on spatial tasks is well established (Cochran and Wheatley 1989; Hegarty and Kozhevnikov 1999; Schofield and Kirby 1994: Tzuriel and Egozi 2010).

Although it did not exclude use of holistic spatial strategies, the paper-and-pencil map format used in the comparison method of instruction encouraged a more linear and analytical method of working through the exercise. For example, the number of McDonald restaurants per city were displayed with the city’s name in a data table in the comparison group versus symbols linked to an absolute location displayed on a digital map in the intervention group. Perhaps the average spatial skill group performed better in the comparison group because they were restricted to more analytical and verbal strategies. Whereas, for the intervention group using GST, participants could employ analytical, verbal, or spatial strategies. The high spatial skill group was better at optimizing “a large repertoire of strategies.”

It has been suggested that individuals with lower spatial ability should benefit most from using GST (Meneghetti et al. 2013). On the other hand, because of cognitive overload that may occur from having to learn new technology simultaneously with spatial thinking strategies, individuals with lower spatial ability may benefit more from static simpler tools, such as paper maps (Bunch and Lloyd 2006; Rossano and Moak 1998). In this case, it may be that the average spatial intervention group experienced cognitive overload when trying to use the technology and applying spatial thinking strategies, while at the same time grappling with unfamiliar content. Thus, they were less successful in learning the content. This group of students, though, had used GST, as an in-class exercise developed as part of the AGSSS GK-12 project, at least five times prior to the study. All of the participants were familiar with GST, specifically Google Earth and GIS layers created in ArcMap. A few software tools or functions would have been novel, but the technology itself was not. As a result, it is unlikely that cognitive overload due to new technology was a factor related to the opposing patterns identified.

Sex

Sex-related differences are frequently found in spatial skills. Males perform consistently and significantly better than females on many spatial tasks, such as 3-dimensional rotation and mechanical abilities (Linn and Peterson 1985). Prior to grouping the participants by spatial skill category and instructional method, no difference between males and females was present in spatial skills or in spatial relations content knowledge. After grouping participants by spatial skill, instructional method, and then by sex; differences by sex were present in the scores for spatial relations content knowledge.

Low spatial skill males performed best in the comparison group on the content-independent item category (19.2 percent increase). They performed the worst in the intervention group on the same item category (10.9 percent decrease). Low spatial males' scores decreased slightly in both instructional groups and on the content-dependent item category. Low spatial females, on the other hand, performed best in the intervention group with a medium increase to scores in both the content-independent and content-dependent item categories (25.0 percent, d=0.87; 17.1 percent, d=0.63, respectively). Low spatial females' scores decreased in the comparison group for both. Following instruction, low spatial skill females in the intervention group had a significantly higher mean score in the content-dependent item category than their comparisons, even though no difference was present in their pretest scores.

Results for the low spatial males indicate no consistent pattern that could infer a more or less effective instructional method. Results for the low spatial females infer that the GST method, utilized in the intervention group, was a more effective instructional method for this group.

Average spatial skill males performed best in the comparison group on the content-dependent item category (20.8 percent increase). Average spatial males performed the worst in the comparison group on the content-independent item category (1.7 percent decrease). Mean gains in scores for the average spatial males in the intervention group demonstrated a reversed trend, they had the greatest gains in scores on the content-independent item category (16.7 percent increase) and very little change in scores on the content-dependent item category (1.0 percent increase).

Average spatial females performed best in the comparison group with a medium increase to scores in both the content-independent and content-dependent item categories (21.7 percent, d=1.00; 8.7 percent, d=0.41, respectively). Average spatial females' scores decreased in the intervention group for both.

Similar to their low spatial male counterparts, results for the average spatial males indicate no consistent pattern that could infer a more or less effective instructional method. In contrast to their low spatial female counterparts, results for the average spatial females infer that the GST method, utilized in the intervention group, was *not* the more effective instructional method for this group. Average spatial females appear to gain more spatial relations content knowledge using the paper-and-pencil static instructional method.

High spatial males demonstrated the greatest gains in scores in the intervention group with a 43.2 percent increase on the content-independent item category. High spatial males in the intervention group had significantly higher posttest scores on the content-independent item category than their high spatial counterparts in the comparison group. High spatial males in the intervention group had significantly higher posttest scores on both item categories than the low spatial males in the intervention group. In the comparison group, high spatial males had moderate gains in the content-dependent item category and a small decrease in the content-independent item category.

High spatial females demonstrated an increase in scores across both instructional groups and for both item categories. The greatest increase in scores was achieved in the intervention group on the content-dependent item category with a statistically significant gain of 36.0 percent (p=0.05). The smallest gain for the high spatial females was also in the intervention group on the content-independent item category (8.0 percent).

Results for the high spatial males and females provide reasonable evidence that individuals with high spatial skill acquire spatial relations content knowledge better with an instructional method that integrates GST. High spatial males experienced a stronger effect for learning with GST as evidenced by the substantially larger gains in scores by males in the intervention group than in the comparison group. Even though high spatial females had the greatest increase of mean score for the content-dependent item category in the intervention group, they also had moderate gains on both item categories in the comparison group.

Interaction between spatial skill level and sex influences the effectiveness of the instructional method. The use of GST, in this case, had no differing effect on low or average spatial males, a positive effect on low spatial females, a negative effect on average spatial females, and a large positive effect on high spatial males and females. Generalizations, however, should be made with caution. Differences in scores pre to posttest for all, except for the high spatial individuals, were not significant, and the twelve groups used for analysis at this level were small, unequal, and had large variations of scores (range in standard deviation was 13.6 to 42.4 percent) for the groups.

From these results, it would appear that choice of instructional method is more influential for low and average spatial females than for low or average spatial males; low spatial females benefiting more from the intervention method and average spatial females benefiting more from the comparison method. And, utilizing GST is substantially influential for high spatial males. High spatial females appear to benefit from either instructional method. Overall, high spatial individuals outperformed their same-sexed low and average spatial skill counterparts in all but one posttest mean score regardless of item category or instructional method, indicating an academic advantage based on pre-intervention level of spatial skills. In addition, high spatial males and females in the intervention group demonstrated greater gains than those in the comparison group, indicating the use of GST is a more effective instructional method for high spatial individuals.

What might explain the striking differences in results between males and females? The explanation could be simply statistics. The groups were too small with too much variation to capture actual trends or patterns between males and females. The trends identified were possibly random and due to chance. The explanation could be that males and females should not be classified so hastily as “boys are better” and “girls are not.” Prior research suggests males, in general, tend to be better spatial thinkers than females (Linn and Peterson 1985). However, other research suggests sex does not strongly influence spatial thinking, rather factors such as socioeconomic status, prior experience, or memory capacity may weigh more substantially on the development of spatial thinking (Caplan et al. 1985; Halpern 2000; Levine et al. 2005).

The distribution of males and females in the low, average, and high spatial groups was similar with no statistical difference between the numbers of males versus females. It can be concluded, therefore, that males and females were equally represented in the three spatial skill groups. In other words, boys were not better than girls in this example. Spatial skill was not influenced by sex or instructional method, but learning outcomes were.

Motivation can influence academic performance and the effect of different instructional methods (Baker and White 2003). The relationship among motivation, investment of mental effort, and effectiveness of different instructional methods is one of the major factors that distinguishes experts and novices. Expert performance research has shown that the amount of deliberate effort to improve performance, or relevant practice, improves performance more so than amount of inattentive experience (van Gog et al. 2005). Deliberate effort to improve performance is shaped by motivation. Participants in this study likely had varying amounts of motivation towards school, the specific class, and/or the instructional unit's content and method, which may have influenced the quality of deliberate effort on the activities and their scores on the posttests.

All classes utilized for the study were honor level geography classes during the spring semester of an academic year. Students who were academically unsuccessful in the honor class during the fall semester or that did not want to be in an honor-level geography course, were not part of the sample. The honor students participating in the study had high motivation for academics, good study habits, and positive attitudes towards geography. Motivation for good academic performance, therefore, was controlled to an extent. Motivation for GST, however, was not. Even though all students in the sample had prior GST classroom experience as a result of being AGSSS participants, the individual females that made up the low spatial intervention group may have had a much higher motivation for using GST than their male counterparts. Likewise, high spatial individuals may have practiced a greater degree of deliberate effort using GST, and thus improved performance, due to a high motivation for the technology combined with an "expert" ability in spatial thinking.

The inconsistent results in learning outcomes, which were influenced by spatial skill, instructional method, and sex; and feasibly by socioeconomic level, prior experience, motivation, spatial language, memory, and other yet to be identified factors, support the importance of differentiated instruction (Tomlinson et al. 2003). Returning to the factors identified in the Spatial Thinking Instructional Model (STIM), only the mental images factor was examined here. Variability in learning outcomes was likely influenced by all six fluid factors, individually and interdependently. The significant gains demonstrated by the high spatial group using GST supports the importance of integrating GST most especially, although not exclusively, for the benefit of high spatial thinkers.

Relationship Between Gains on Spatial Skills and Gains on Spatial Relations Content Knowledge

Hypothetically, if high spatial skill predicts gains in spatial relations content knowledge, then gains in spatial skills may also be associated with gains in content knowledge. A scatterplot graph and correlation were used to explore the potential relationship between changes to spatial skill and changes to spatial relations content knowledge. No linear relationship was evident between changes to spatial skills pre to posttest and changes to content knowledge pre to posttest.

This result contradicts prior work that found a robust effect from training for spatial visualization with an associated gain in geoscience content knowledge (Pilburn et al. 2005). Correlational studies that examine the influence of training spatial skills on acquiring content knowledge, such as Pilburn's, are sparse. His research suggests that geoscience content learning can be improved as a result of improved spatial thinking. Results of the current study suggest a lack of transfer of newly acquired skills to understanding a spatially dependent concept. In other words, geography content learning was not improved as a result of improved spatial thinking. Geography content learning was, however, enhanced by high initiatory levels of spatial thinking.

SELF-EFFICACY FOR SPATIAL THINKING

Self-efficacy is sometimes a predictor for skills and/or abilities (Bandura 1978). Individuals with a high level of confidence for a task or skill tend to perform better at that task than individuals with a low level of confidence. For example, studies have shown self-efficacy to be a significant predictor of technology use (Kinzie, Delcourt and Powers 1994), student attitudes towards technology (Baker and White 2003), willingness to engage in inquiry and data gathering (Ketelhut 2007), and desirability of learning new skills (Zhang and Espinoza 1998). Specific to spatial abilities, prior work has likewise shown a correlation between self-efficacy beliefs for spatial skills and actual performance for spatial skills on a standardized test (Paunonen and Hong 2010).

In general, however, past research has understood self-efficacy as a mediator for learning without testing for such a relationship (Williams and Williams 2010). Evaluating the significance of self-efficacy in the context of learning a spatially dependent topic could provide a better understanding of the impact of self-efficacy on acquiring content knowledge and help to identify factors that may account for the differences observed in the spatial relations content knowledge scores.

A survey instrument was modified from the Santa Barbara Sense of Direction survey (Hegarty et al. 2002) and administered once, prior to instruction, for the purposes of characterizing participants' self-efficacy, quantifying self-efficacy for environmental (large space) spatial tasks, and then analyzing self-efficacy scores and categories in relation to spatial skill scores and content knowledge scores. Quantitative comparison of item responses, using principal component analysis (PCA), confirmed four factors qualitatively labeled by the researcher as: 1) location, distance, direction; 2) navigation; 3) map reading; and 4) spatial memory. However, because the 17 items, as a whole, displayed an acceptable level of internal reliability ($\alpha = 0.78$) and the distribution of scores for the sum of the 17 items closely fit the assumptions for normal distribution; the intact 17 item scale, rather than the separate factors, was used intact to characterize participants' self-efficacy and to define spatial survey categories.

A difference between what the participants believed and what they practiced was found. Participants scored themselves relatively high on items that indicated they *believed* they were good at specific spatial thinking tasks such as thinking visually, having a very good mental map of their environment, and being very good at reading maps. On the other hand, they scored themselves relatively low on items that indicated a preference or enjoyment for *doing* specific spatial thinking tasks such as thinking of their environment in terms of cardinal directions, enjoying reading maps, enjoying giving directions, or planning the navigation for long trips. In voluntary situations, people tend to engage in tasks in which they feel confident and avoid those in which they do not (Pajares 2002). It is unexpected, then, to find a dichotomy between beliefs and practices. Several factors may assist in explaining these results.

One, males tend to have a higher self-confidence for certain skills, for example mathematics, than females, even though scores for males and females may be equivalent (Hargreaves, Homer, and Swinnerton 2008). The conflicting results observed between beliefs and practices could be a result of the aggregated scores of males and females. Averages can hide differences in a sample. It is possible that a minority of participants could be so strongly different as to create a misleading average. Two, a large number of the participants had not started driving automobiles. Thirty percent (n = 33) were 15 years of age and not old enough to obtain a driver's license, and of the remaining who were of age to drive, it is likely that some had not yet elected to do so. Many of the items on the survey could be influenced by experiences driving an automobile. The dichotomy between observed practices—they have watched others navigate and read maps—and performed practices might explain why they believe they *would* be good at something even though they have not had reason to actually *do* that something.

Sex differences were explored further by categorizing the participants in one of three groups based on the sum score of the 17-item survey. Using a histogram and frequency table of the spatial survey sum scale, three categories were created and labeled low spatial survey, average spatial survey, and high spatial survey. Participants were equally grouped in the three categories: low (n = 36), average (n = 37), and high (n = 36). The distribution of males and females in the spatial survey categories, however, was unequal. More males than females were in the high spatial survey category, and more females than males were in the low spatial survey category.

Spatial survey categories were compared to spatial skill categories by sex. High spatial skill males were more likely to rate themselves high on the survey. Eleven out of 20 high spatial males (55 percent) rated themselves high spatial on the survey. High spatial females, on the other hand, were more likely to rate themselves low on the survey. Eight out of 16 high spatial females (50 percent) rated themselves low spatial. Other combinations had relatively equal numbers, although males' self-ranking in the survey matched their spatial skill category more often than females' matched. This implies males were somewhat more accurate in their self-assessment than the females regarding spatial skills, especially in the high spatial skill category.

Self-Efficacy for Spatial Thinking and Changes to Spatial Skills

All three spatial survey groups demonstrated positive gains on average accuracy for spatial skills. Significant gains were found pre to posttest for the low and the average spatial survey group. The spatial survey categories were further divided by sex. No difference existed for the six groups (spatial survey category by sex category) for average accuracy scores on pre spatial skills or post spatial skills. No sex difference was present on pretest scores or on posttest scores. When examining gains pretest to posttest in spatial skill scores, only low spatial survey and average spatial survey females had statistically significant gains. The other groups, the high spatial survey females and all three male groups, had small positive, but insignificant, gains.

The females in this study, appear to have underestimated their spatial skills whereas the males may have overestimated their skills. The significant gains pretest to posttest in spatial skills for females that ranked themselves lower in the spatial survey indicate that practice and training may have more of a positive effect on spatial skills for females than for males. This finding is supported by other research examining sex differences in self-efficacy. Although girls tend to rank themselves lower in self-efficacy than boys on many attributes or skills (e.g., spatial skills or learning a new math task), sex differences are often not present on measures of that attribute following training (Schunk and Lilly 1984). In this study, even though females ranked themselves significantly lower on average than the males for spatial self-efficacy (56.2 percent and 61.8 percent, respectively; p=0.01), and even though females scored slightly lower on average than the males in the pretests for spatial skills (78.0 percent and 79.8 percent, respectively), after instruction, females surpassed males with a higher spatial skill average (84.0 percent and 81.5 percent, respectively). This was especially evident for the average spatial survey group where the males average accuracy score for spatial skills remained practically unchanged pre to post at 78.8 percent, while the females in this group increased significantly from 74.0 percent to 83.2 percent.

For males, self-efficacy for environmental (large space) spatial tasks was somewhat of a predictor for spatial skills. It was not a predictor for females' spatial skills.

Self-Efficacy for Spatial Thinking and Changes in Spatial Relations Content Knowledge

In order to explore the effect of self-efficacy on spatial relations content knowledge, content knowledge scores were compared among the three spatial survey categories using analysis of variance. Scores were divided into two item categories: content-dependent and content-independent. The control group was excluded from this step of the analysis because they did not receive any instruction about spatial thinking strategies or central place theory.

No one spatial survey group outshined the others in regards to content scores. In some instances the high spatial survey group had the highest mean score (e.g., in the pre content-independent item category) and other times the low spatial survey group did (e.g., in the post content-independent item category). No statistical difference was present for pretest or posttest content scores. All three spatial survey groups had small to medium gains. Significant gains in scores were present for the low and the average spatial survey group on the content-independent item category. Changes to content knowledge scores based on spatial survey categories demonstrate a different pattern from the pattern based on spatial skill, where the high spatial skill group consistently demonstrated greater *gains* in content knowledge than the low or average spatial skill groups. In contrast to prior research, these results infer no relationship between self-efficacy for environmental (large space) spatial tasks and spatial relations content knowledge (Paunonen and Hong 2010).

Spatial survey categories were then arranged by sex. Content scores were compared among the resulting six groups to explore potential differences between males and females. No difference was present in the six groups' pretest scores or posttest scores. One group, average spatial survey females, scored significantly higher on the posttest than on the pretest for content-dependent items. The other groups had a moderately higher mean score on the posttests than on the pretests, but no clear pattern of male advantage or female advantage based on self-efficacy level was present.

Spatial survey categories, grouped by sex, were further divided by instructional group. Content scores were compared among the resulting twelve groups in order to explore potential differences in scores influenced by the instructional method. No difference was present for the 12 groups' pretest scores or posttest scores. One group, average spatial survey females in the intervention group, scored significantly higher on the posttest for content-dependent items. In general, average and high spatial survey males and females in the intervention group had greater gains in scores on the content-dependent item category than their counterparts in the comparison group.

From these results, the use of GST appears to positively influence spatial relations content knowledge for the average and high spatial survey groups. In addition, sex differences that were evident in the self-efficacy categories (i.e., more males than females ranked in the high spatial survey group), were not evident in scores on the spatial relations content test. The relationship between self-efficacy beliefs and academic self-regulation is a prominent area of research (Pajares 2002). Current thinking on this relationship contends that self-efficacy beliefs are accurate predictors of motivational and academic success (Zimmerman, Bandura, and Martinez-Pons 1992). One finding was that this contention was not the case here. Self-efficacy beliefs did not predict academic success. This may be due to a poor match between the instrument used to measure self-efficacy and the spatial thinking required by the spatial relations content test. The spatial survey quantified self-efficacy for environmental (large space) spatial tasks. That may not have been the same type of task measured in the content tests. Or, an alternative explanation, the results of this study may not match theoretical predictions because self-efficacy for spatial thinking may have no bearing on motivation or academic success related to learning spatially dependent concepts.

A second finding is that differences between males and females for spatial thinking self-efficacy were present, but these differences did not affect academic performance. The higher frequency of high spatial survey males may be due to the male tendency to be more "self-congratulatory" in self-reported responses. Whereas the higher frequency of low spatial survey females can be attributed to the female tendency to be more humble. Boys are more likely than girls to assert confidence in skills they may not possess and to assert overconfidence in skills they genuinely do possess (Wigfield, Eccles, and Pintrich 1996). Results in this study concur with prior research. Males asserted more confidence for spatial tasks and habits and were more accurate, than females, in their self-assessments. Females asserted more uncertainty for spatial tasks and habits and were less accurate in their self-assessments.

LIMITATIONS OF THE STUDY

Education research is an applied field of inquiry. It is "an enterprise fundamentally aimed at bringing theoretical understanding to practical problem solving" with two related purposes: (1) add to the understanding of education-related phenomena, and (2) inform policy decisions with the intent to improve educational practices (National Research Council 2002, 83). As an applied research project on human beings in an authentic context, certain limitations to this study were inherent. These include limitations to validity, reliability, objectivity in relation to bias, generalizability of the results, and level of certainty with which research conclusions can be made.

The study sample was recruited from a population of 10th grade honor students from a high school in a relatively affluent city close to a top American research university (Lombardi et al. 2012). The ethnic and academic composition of the sample was not representative of the regional or state population. In addition, the sample size would be considered modest by typical research standards. Limitations to the generalizability of the findings based on sample size and composition must be considered.

The instructional unit was taught by the researcher and by a colleague who was a geography graduate research assistant. Scripts were utilized in an effort to keep instruction of the content and explanation of the tasks similar between the intervention and comparison groups. The researcher and the colleague met three times prior to administering the instructional unit to rehearse the script and to review procedural steps for the activities. In addition, two external researchers informally observed instruction and student interaction between the groups. The observers spent time watching the intervention group and the comparison group. Both reported similar levels of teacher-student interaction and student participation between the groups. Even though these measures were used to limit bias and confounding variables, it is possible that outcomes were influenced by differences in teaching style, demeanor, and/or student-teacher interactions.

Published instruments were not available to measure content knowledge of central place theory and spatial thinking. This resulted in the need to create one. The development of a content specific assessment instrument is challenging. Items created for the instrument were evaluated by several geography experts who agreed the items required spatial thinking and contained content related to central place theory. This contributed content validity to the instrument. However, several limitations related to the *scale* of the instrument should be noted.

Three a priori item categories were identified to guide development of the instrument: content-independent, content-dependent, and task-based. Content-independent and dependent items were multiple choice. Careful attention was given to creating the multiple choice items with an equivalent level of difficulty between the pretest and the posttest using a taxonomy of spatial thinking (Jo, Bednarz, and Metoyer 2010).

Two item categories were calculated from the multiple choice items by creating a percent average score. The percent average score was calculated by taking a sum of correct items, by item category, dividing that sum by the maximum points possible for that item category, and multiplying by 100. Flaws in the grouping of the items, however, became evident during data analysis. Specifically, the factors required a finer scale, a more equal scale, and a more reliable scale.

Rough scale was due to a limited number of items, four in the pretest and six in the posttest. A finer scale could be created by increasing the number of multiple choice items.

The two item categories were unequal. The pretest had two items per item category, for a total of four, and the posttest had three per item category, for a total of six. This created unequal intervals in the resulting categories. Equal scales could be created by establishing an equal number of items for each item category on both tests.

The items lacked internal reliability. Three items were ambiguous and difficult to classify as either content-independent or content-dependent (e.g., Item 2 on the pretest and Item 1 on both). This was managed for Item 1 by determining it was *predominantly* content-independent. It was included in the scoring for only the content-independent item category. On the other hand, two responses to Item 2 were feasibly correct. Response “B” would be most accurate if the student was responding with a knowledge of central place theory, and “B” was the planned correct response. Response “D” could also be justified, utilizing a visual interpretation of the spatial patterns on the map. For this reason, a response of “B” was given full credit (2 points) and the score was included in the content-dependent item category, and a response of “D” was given partial credit (1 point) and the score was included in the content-independent item category.

Difficulty level for the task-based items on the content test were not the same between the pretest and the posttest. The posttest items proved to be more time consuming and difficult. As a consequence, results from the task-based items were not used in analysis for this study.

Weaknesses in the spatial relations content test limit the level of certainty with which research conclusions can be made. It is not possible to statistically categorize (through factor analysis) the content-independent and content-dependent item categories due to the rough scale. Therefore, the item categories are qualitatively constructed categories and may not measure two separate factors. In addition, internal reliability measured as a correlation coefficient is not an appropriate method with a small number of items per item category. Finally, level of certainty related to the spatial skill categories is shaky due to the course scale of the content test. A difference in score on one item could potentially shift an individual from one category to another.

The content test could be improved upon through an iterative cycle of development, administration, revision, and statistical confirmation. However, the applicability for such an instrument beyond this study would be small, if not absent. Proper development of a concept inventory or content knowledge test, especially one that measures spatial thinking in a geographic context, requires substantial time and resources. More individuals are working to expand upon this by properly developing assessment tools specific to geography education (Huynh and Sharpe 2013; Lee and Bednarz 2009). Future research stemming from this project would benefit from using a published reliable instrument as the measure for spatial relations content knowledge.

SUGGESTIONS FOR FUTURE RESEARCH

Research on the use of GST to support spatial thinking is a complex and dynamic environment. Six fluid factors were identified in the literature review that influence the development of spatial thinking: (1) self-efficacy for spatial skills, (2) metacognition, (3) prior spatial thinking practice and play, (4) spatial language, (5) memory, and (6) mental images. This study examined the last, mental images. Specifically, the influence of using GST as a tool to support creation of mental images and, thus, facilitation of spatial thinking was explored. The influence of students' learning preference, cognitive style, prior experiences, and initial levels of spatial thinking ability play a role in the effectiveness of using GST to create and employ mental images (Mayer and Massa 2003). Future research should continue to examine the importance of these six factors on spatial thinking. Future research should also begin to develop a synthesis of the factors, examining spatial thinking from a more integrated model of instruction. In order to better understand how spatial thinking may be improved upon in a formal educational setting, it is necessary to understand how these factors interact and how strategies for teaching the most malleable of these factors can be integrated into normal classroom practices.

Much education research focuses on outcomes from one event. Follow-up to this study could incorporate a repeated measures longitudinal design. In the current study, participants received one training episode using GST with explicit attention to spatial thinking. Future work could model the experimental design and instructional activity used for this study, but include multiple exposures to GST through several activities over the course of one academic year.

Assessment of spatial thinking in the context of a specific concept or academic discipline is an under-exploited area of research. Development of valid and reliable instruments that can measure changes to students' skills and knowledge is of critical importance. The credibility and applicability of results is dependent upon the quality of the instruments used. Even though valid instruments exist that measure spatial skills future research should expand upon, and make easily available, instruments that measure spatial thinking along with content knowledge. Such instruments could help identify and validate effective strategies for teaching content with spatial thinking.

Education equity is a major area of concern and research in the education community. It is sometimes considered as a measure of equitable opportunity to learn, and it is dependent upon fairness and inclusion. How, when students are diverse with widely varying backgrounds, can one method of instruction be the fairest and the most inclusive to the largest number of students? The following are a few cases of potential sources of inequity noted by the researcher in this study: some students had more access to GST and technology outside of school; some students had prior experience driving cars; and some students preferred working with paper-and-pencil maps whereas others preferred working on the computer. Students should be provided an equal opportunity to learn new content absent of limitations or biases based on prior experiences or learning preferences.

Results from this study demonstrated, to an extent, the truism of "the more you know, the easier it is to learn more." However, it also exposed large variations in outcomes for the two instructional methods. Future research could examine what method of instruction is most effective for different types of learners (e.g., low spatial thinkers versus high spatial thinkers). Or, perhaps a more beneficial area of research could explore integrated models of instruction (such as the *Spatial Thinking Instructional Model)* that combines different teaching methods and strategies for a lesson or activity. Using an integrated model of instruction, all students would receive the same instruction, but each student would benefit individually more from one method or strategy versus another.

CONCLUSIONS

In conclusion, each of the research questions are briefly answered, initial assumptions are re-visited, new knowledge gained related to the STIM conceptual framework is discussed, and implications for K-12 geography education are stated. The first research question asked, what is the effect of using GST on students' spatial thinking skills? Geospatial technologies did *not* have an effect on students' spatial thinking skills in this study.

The second research question asked, what is the effect of using GST on students' content knowledge of a spatial concept in geography? Students utilizing GST during the instruction of central place theory demonstrated greater gains in content knowledge than the students utilizing paper-and-pencil maps. Use of GST is a more effective method for teaching a spatially dependent concept than the traditional paper maps.

The third research question asked, what is the relationship among spatial thinking skills, self-attitudes towards spatial and navigational abilities, and change in students' content knowledge of a spatially dependent concept? Two notable relationships were evident. Students with a high level of spatial skill prior to instruction had an advantage in regards to performance on the spatial relations content test. And, students with a high level of spatial skill performed better when using GST than when using paper maps. This was especially true for the high spatial males. Using GST to teach a spatially dependent concept is most beneficial to students that possess high spatial skills. The link between thinking spatially and thinking geographically is apparent. Higher levels of spatial thinking are correlated with a superior ability for thinking geographically. Other insignificant trends related to self-attitudes, instructional methods, and spatial skills were identified, but no other relationships were remarkable.

Assumptions, informed by the literature, were made for the theoretical framework of this study. Here, some of these assumptions are re-visited and discussed in the context of findings. First, the use of GST was assumed to have a positive impact on spatial skills. This assumption was not supported. Use of GST had no effect on students' spatial skills. All groups had similar gains in spatial visualization skills, including the control group. Re-testing did have a positive effect on spatial skills. Improvement from training spatial skills is well supported in the literature. Therefore, the gains seen in spatial skills were most likely due to a training effect established by the repeated testing.

It was assumed that gains in spatial skills would be positively correlated with gains in content knowledge. This assumption was not supported. Gains in spatial skills had no relationship to gains in content knowledge. It was also assumed that high spatial skills would predict better performance on the content knowledge test. This assumption was supported. In fact, only the high spatial group had significant gains on the spatial relations content test.

It was assumed sex differences would be present in spatial skills and in content test outcomes. More specifically, males were expected to outperform females. This assumption was not supported. Sex differences were neither present in the pretest scores nor in the posttests scores. In addition, no significant interaction effects were present between sex and instructional method. However, differences in gains between males and females on the content test were noticeable. And, high spatial males showed more of an inclination for the GST method. This implies males and females were interacting with the content and instructional method differently. Males, however, were not any better than females in regards to their spatial skills or content knowledge.

The Spatial Thinking Instructional Model is a conceptual framework that proposes six fluid factors influencing development of spatial thinking: self-efficacy for spatial skills, metacognition, prior spatial thinking practice and play, spatial language, memory, and mental images. It is “instructional” because it focuses on skills and abilities that can be fostered by explicit and intentional instruction. This study focused on the instructional influence of one factor, mental images. Future research should continue to explore the impact of mental images on spatial thinking and the effect GST has on the utilization of mental images. Each fluid factor could be explored further as an unconnected variable using a method similar to that utilized in this study. Alternatively, future research could examine the interconnections and covariance among the six factors and their combined effect on spatial thinking. In this way, the STIM can serve as a framework for future research concerning spatial thinking instruction and development and help place the research results in context with the results presented here.

Implications for K-12 geography education are many. Spatial thinking is an important, yet unrecognized, cognitive skill that has a substantial influence on student learning. Students with high spatial thinking skills are better prepared to learn spatially dependent concepts. Yet, even for motivated and academically gifted students, the ability to think spatially varies greatly. In addition, spatial thinking is an amalgam of skills and processes. It cannot be taught through traditional drills or repetition. Geospatial technologies can extend students' abilities to think spatially and understand geographic phenomena. But, GST is also an amalgam of many tools and processes. It should not be assumed that GST, in itself, will improve spatial thinking or content knowledge in isolation of explicit attention to spatial thinking strategies and integration of geographic inquiry.

It is recommended, based on evidence from this study, that GST should be integrated into instruction of spatially dependent concepts. However, in addition to teaching *with* GST, teachers should scaffold the instruction into an authentic problem-solving activity utilizing reform-based teaching methods. Examples may include one or more of the following: collaborative teams of students, deliberate practice on spatial skills needed for success using GST (for example, a mini-session on orientation), reference guides provided for spatial vocabulary, or structured assignments to promote metacognition about the activity and student's own spatial thinking during the activity. Students learn in a variety of ways and require an astounding amount of cognitive tools to become more effective learners.

Spatial thinking is but one cognitive tool, but it is an increasingly important one. Geospatial technologies have become ubiquitous and location matters now more than ever. The widespread availability of GST, however, does not imply that teachers can integrate these technologies effectively or that students can use them competently.

Society is awash in spatial data and GST yet lacks the spatial thinking needed to use GST to solve problems, make decisions, or affect policy. Thus, the recommendation here is that K-12 geography education should advance an integrated model of instruction that emphasizes teaching content with GST for the purpose of promoting inquiry, spatial thinking, and geographic content knowledge.

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APPENDIX A

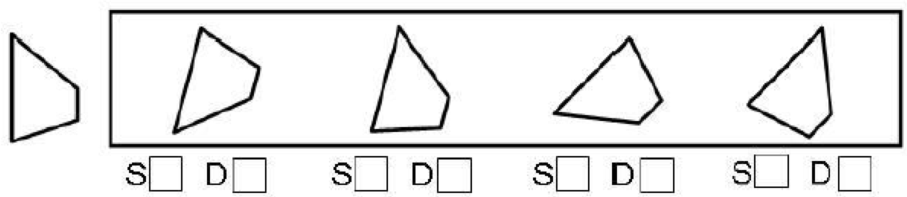
2-D VISUALIZATION PRETEST

Research #: _________

Visualization

Practice Item:

Observe the character in the left column. Mark the item(s) in the same row as either S (same) or D (different). Objects may be rotated but may not be flipped (mirror-image) in order to be considered the same.



Note: This section is time-limited to 2 minutes.

Research #: ________

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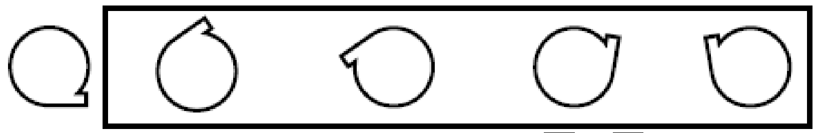

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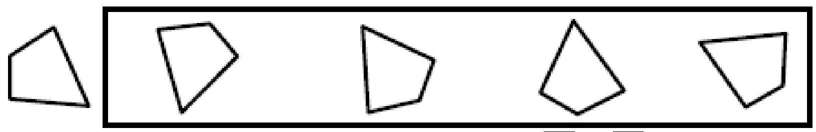

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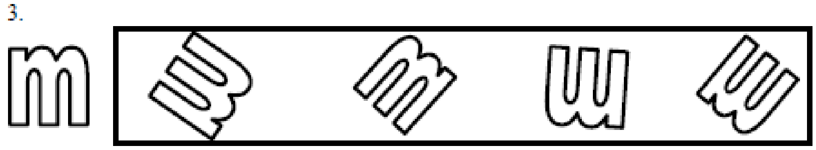

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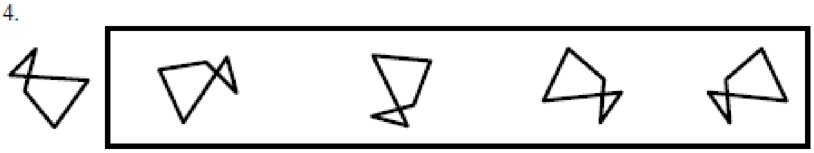

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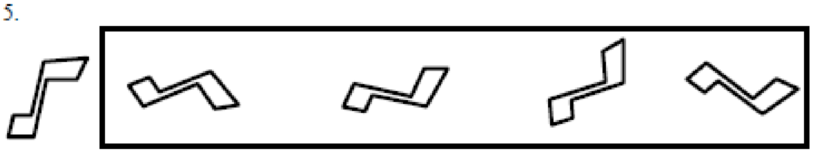

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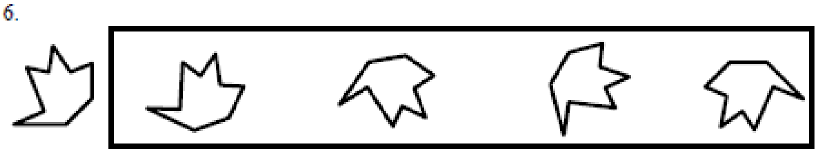

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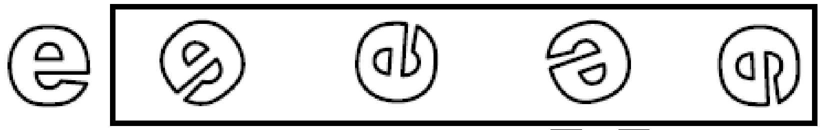

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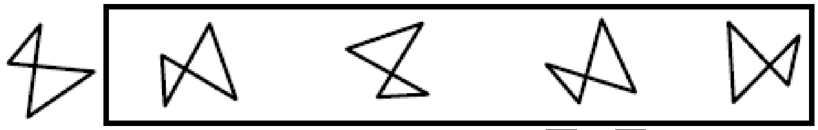

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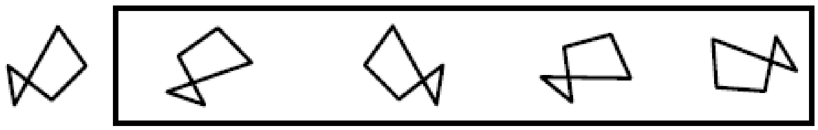

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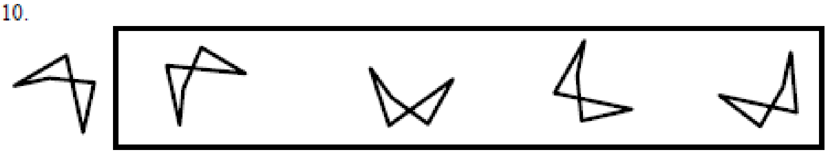

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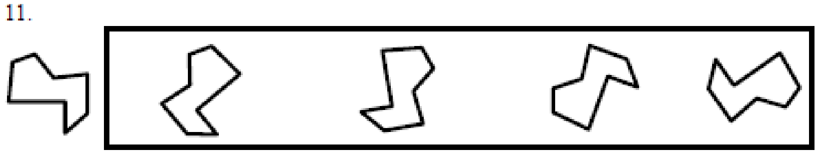

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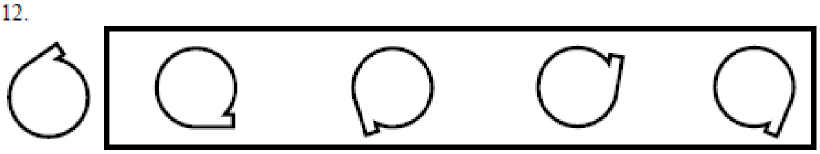

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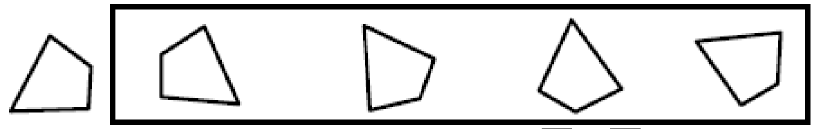

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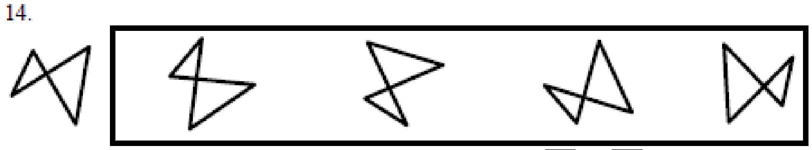

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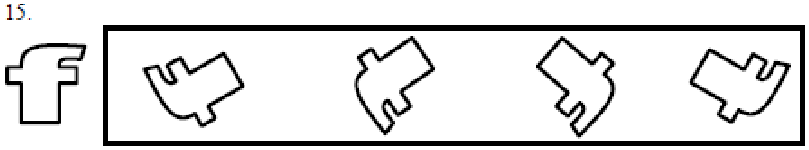

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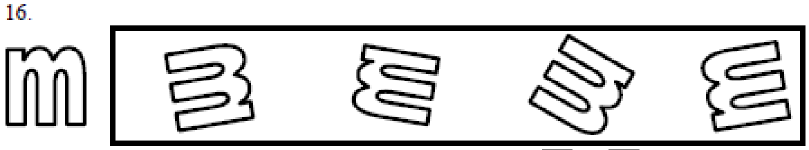

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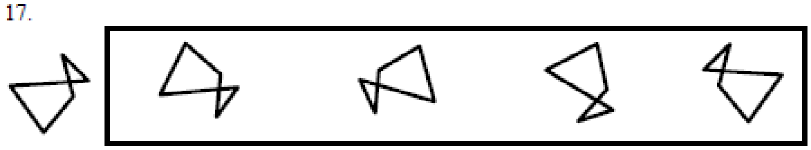

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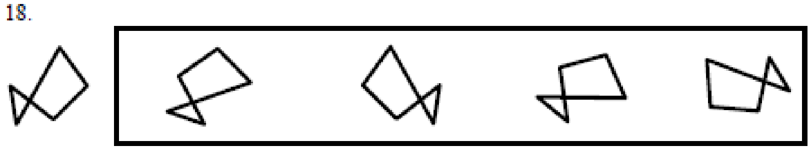

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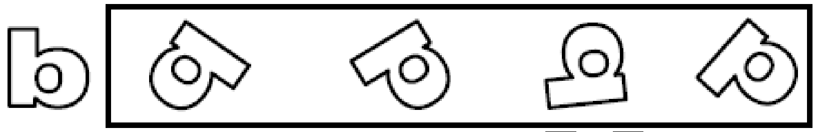

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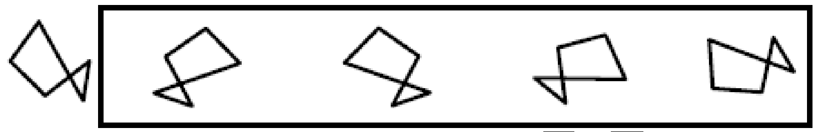

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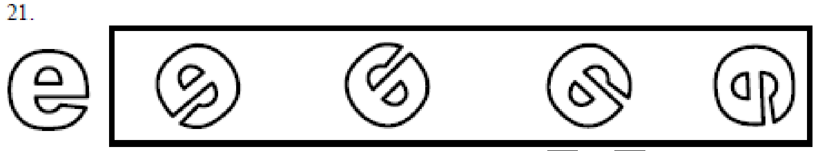

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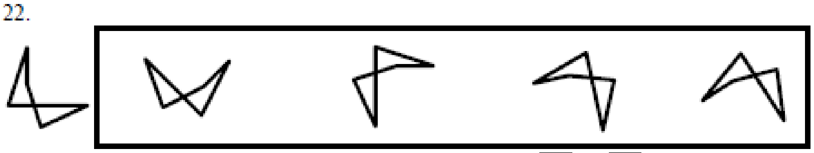

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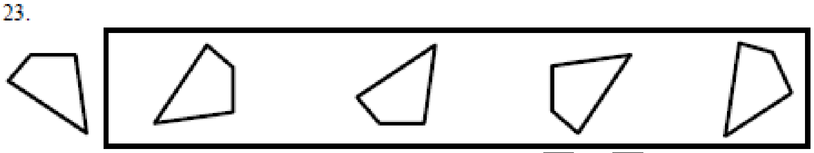

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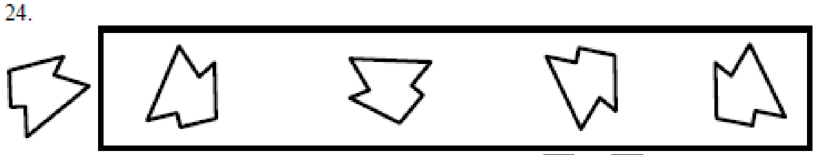

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APPENDIX B

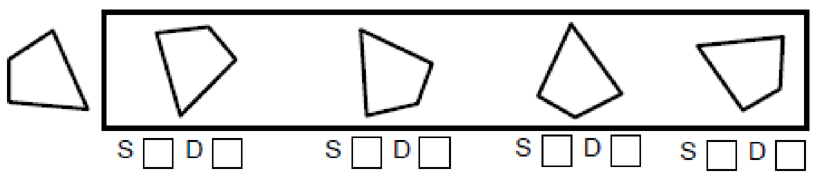
2-D VISUALIZATION POSTTEST

Research ID#: __________

Visualization

Practice Item:

Observe the character in the left column. Mark the item(s) in the same row as either S (same) or D (different). Objects may be rotated but may not be flipped (mirror-image) in order to be considered the same.



Note: This section is time-limited to 2 minutes.

1

Research ID#: ___________

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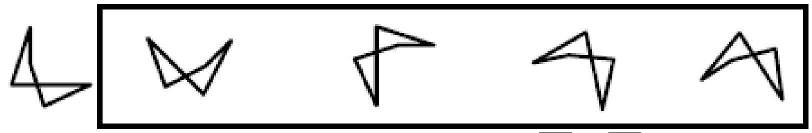
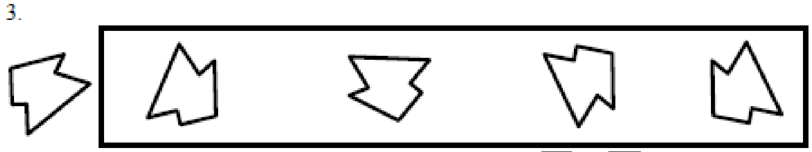


S ☐ D ☐ S ☐ D ☐ S ☐ D ☐ S ☐ D ☐

2.

S ☐ D ☐ S ☐ D ☐ S ☐ D ☐ S ☐ D ☐

3.



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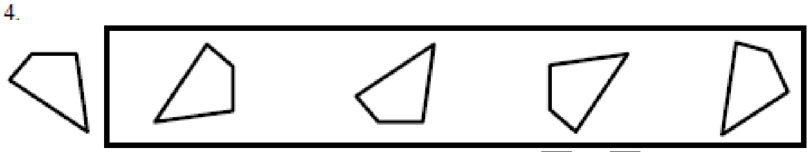

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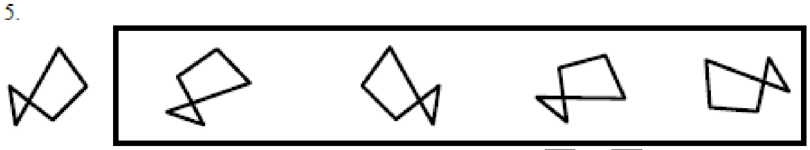

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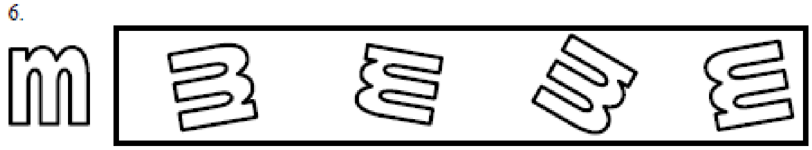

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Research ID#: __________

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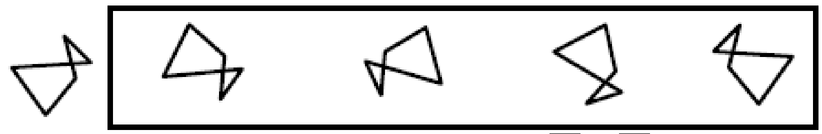

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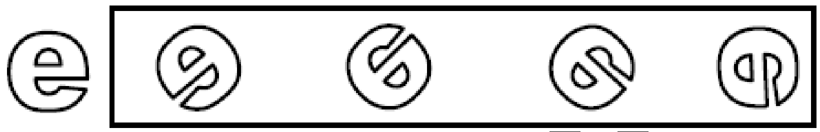

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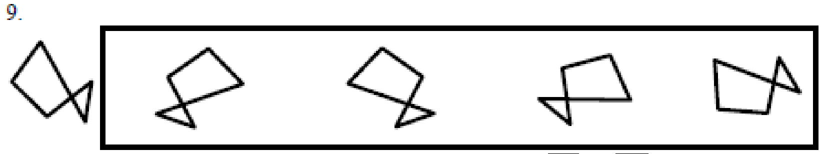

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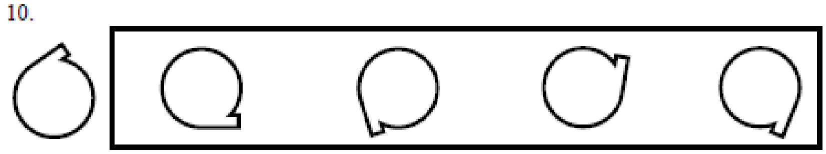

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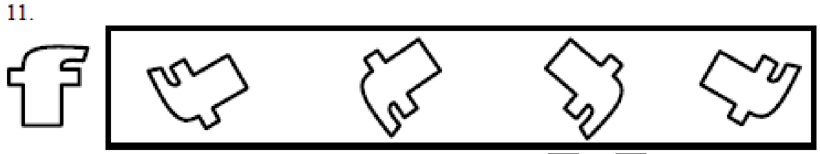

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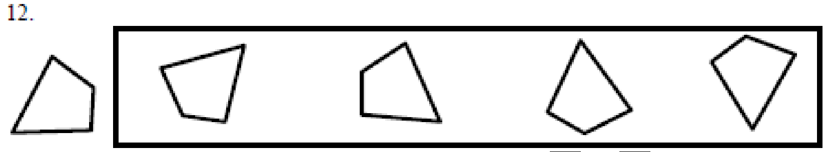

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Research ID#: __________

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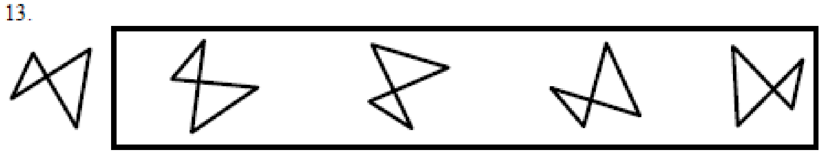

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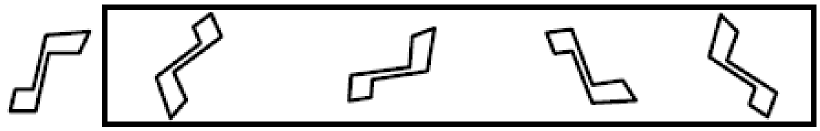

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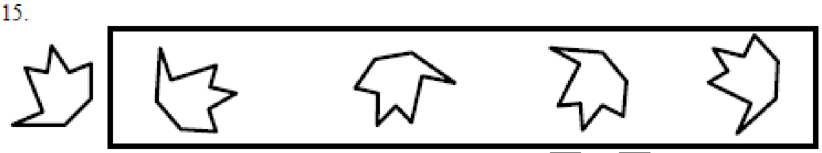

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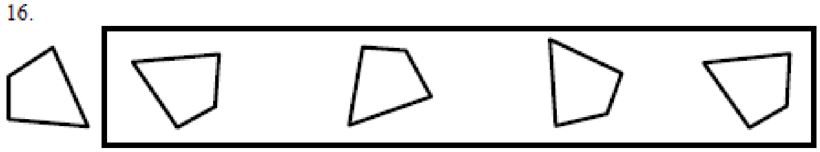

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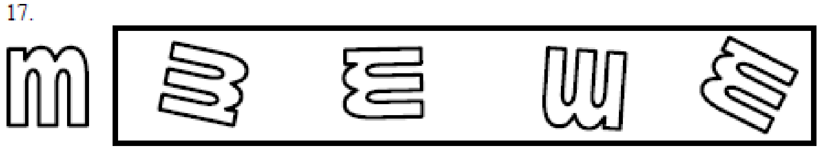

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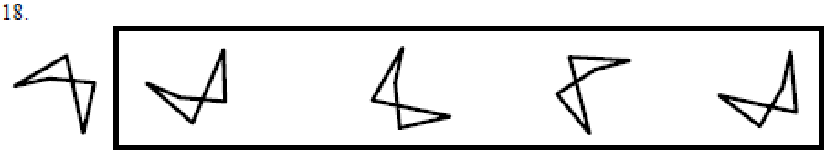

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Research ID#: __________

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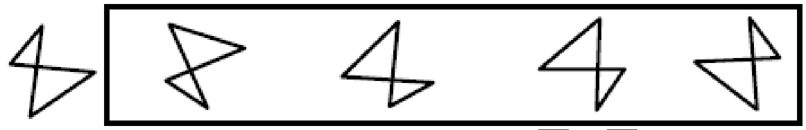

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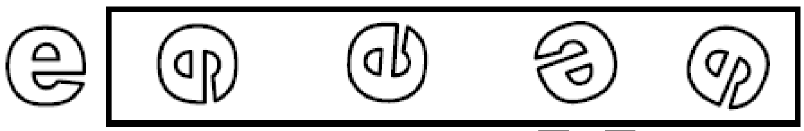

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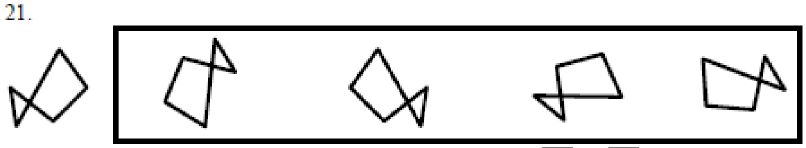

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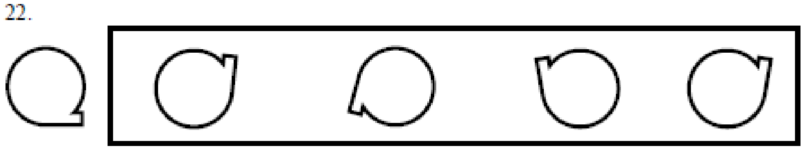

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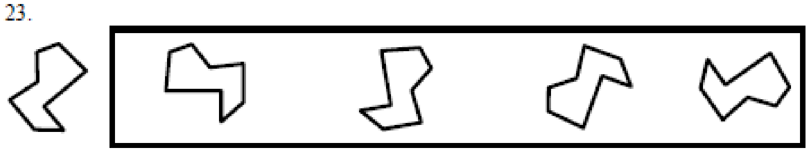

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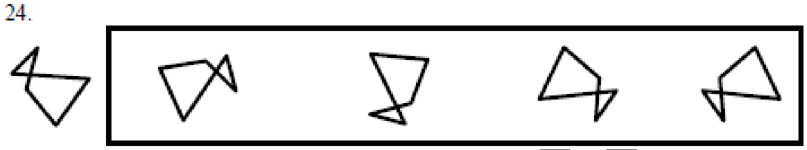

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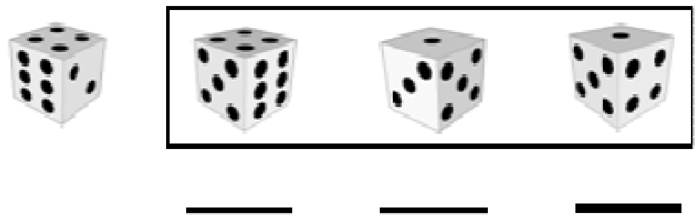
APPENDIX C

3-D VISUALIZATION PRETEST

Research #: ________

Practice Item:

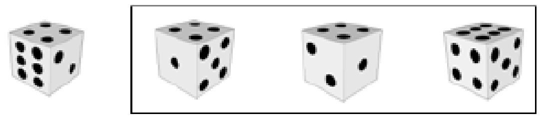
Observe the cube in the left column. Assume that the cube rotates only one face at a time. Use the space below each object to the right and label each object with the correct order of rotations; 1, 2, or 3. You will use 1, 2, and 3 one time for each item.

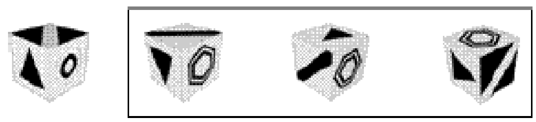


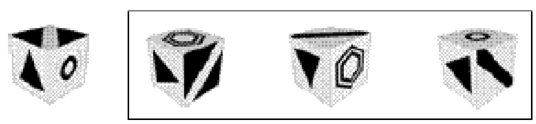
Note: This section is time-limited to 2 minutes.

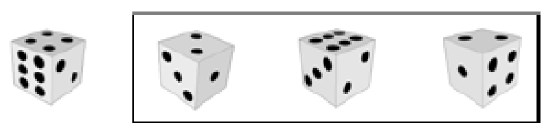
6

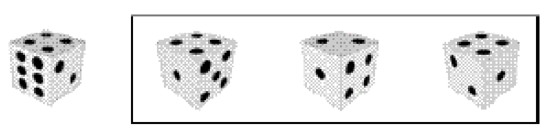
Research #: ________

1. 

2. 

3. 

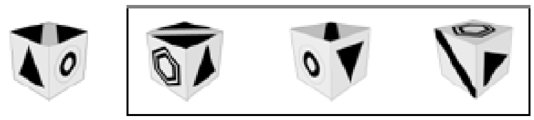
4. 

5. 

7

Research #: __________

6.



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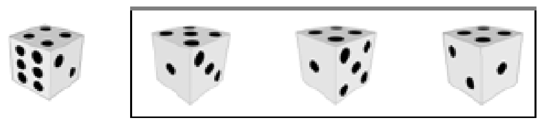

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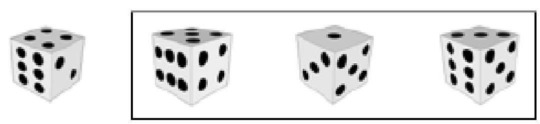

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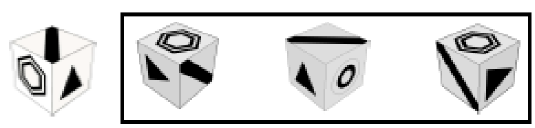

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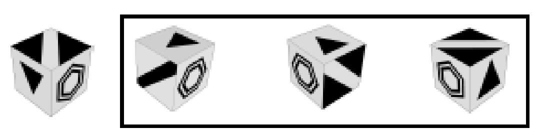
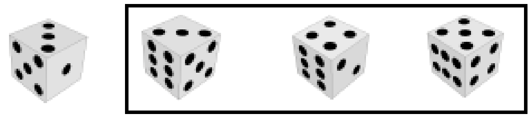


11. 

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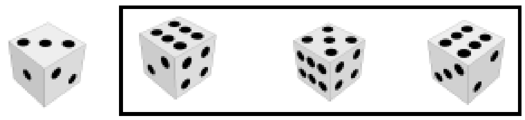
12. 

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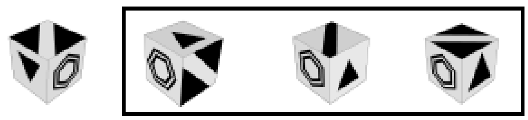
13. 

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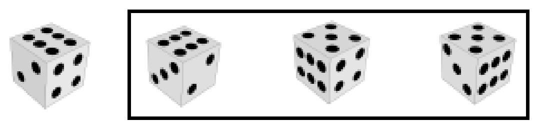
14. 

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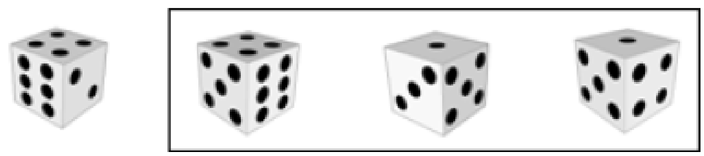
APPENDIX D

3-D VISUALIZATION POSTTEST

Research ID#: __________

Practice Item:

Observe the cube in the left column. Assume that the cube rotates only one face at a time. Use the space below each object to the right and label each object with the correct order of rotations; 1, 2, or 3. You will use 1, 2, and 3 one time for each item.



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Note: This section is time-limited to 2 minutes.

Research ID#: __________

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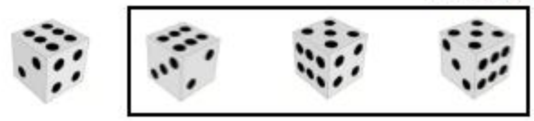

___ ___ ___

2.

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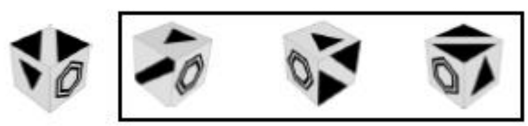
4.



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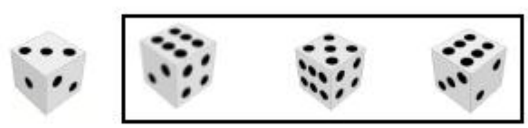
5.



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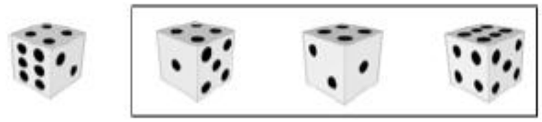
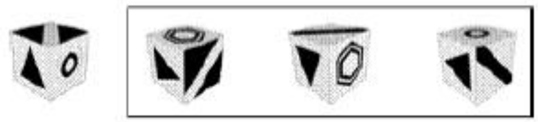
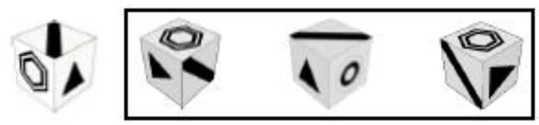
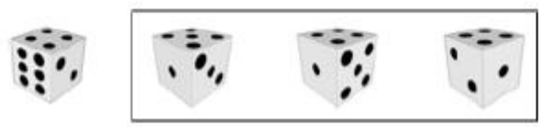
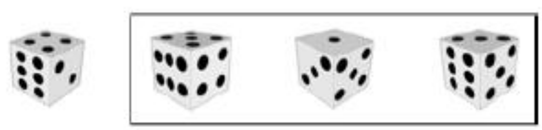
Research ID#: __________

6. 

7. 

8. 

9. 

10. 

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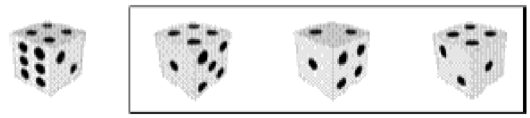
Research ID#: __________

11. 

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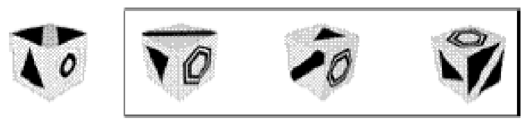
12. 

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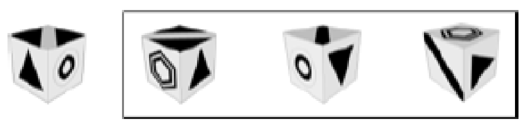
13. 

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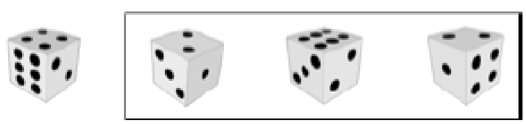
14. 

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APPENDIX E

SPATIAL ORIENTATION PRETEST/POSTTEST

Research ID#: __________

Practice Item:

This is a test of your ability to imagine different perspectives or orientations in space.

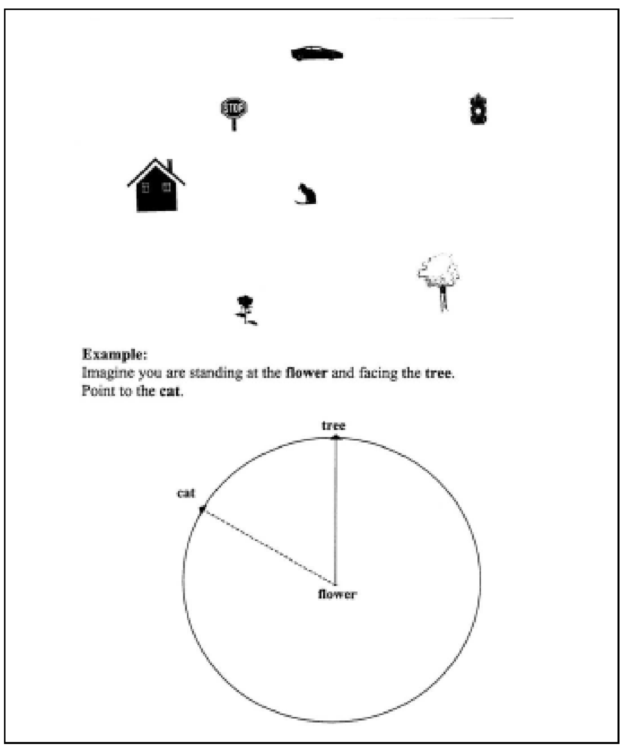
For the questions on each page, you should imagine that you are standing at one object in the array (named at the center of the circle) and facing another object (named on the edge of the circle). Your task is to draw an arrow to indicate the direction you would point from your imagined position and orientation to the third object

There are **20 items** in this test, **two on each page**. For each item, the array of objects is shown at the top of the page and the answer circles are shown at the bottom.

Please **do not pick up or turn the test booklet**, and **do not make any marks on the maps**.

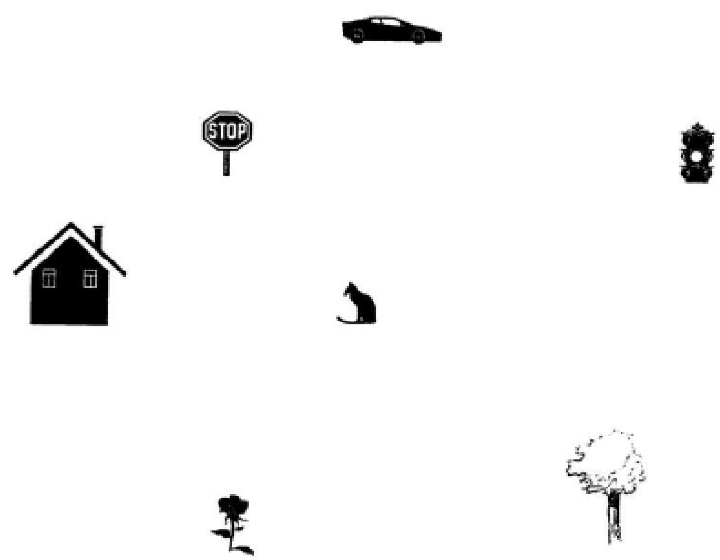
Look at the example below. Your task is to draw a second arrow in the circle to indicate the direction you would have to point in order to **point to the cat**.

This section is **time-limited to 2 minutes**.



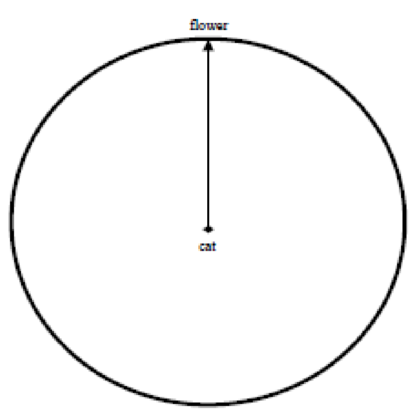
1

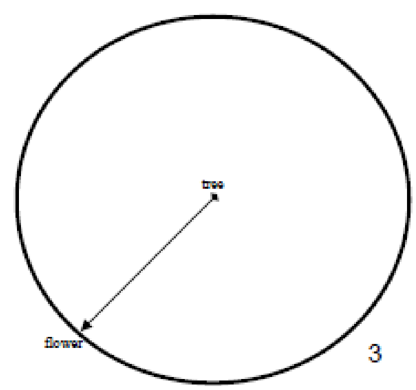
Adapted from Hegarty & Waller (2004) Perspective Taking/Spatial Orientation Test



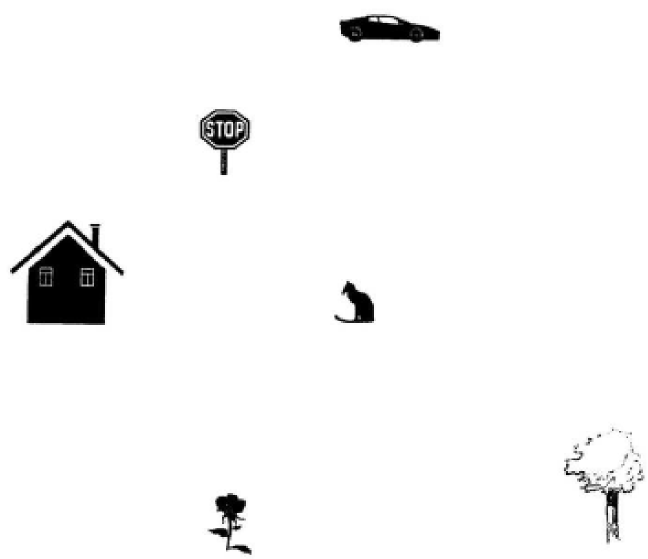
1. Imagine you are standing at the **cat** and facing the **flower**.
 Point to the **stop sign**.

2. Imagine you are standing at the **tree** and facing the **flower**.
 Point to the **traffic light**.



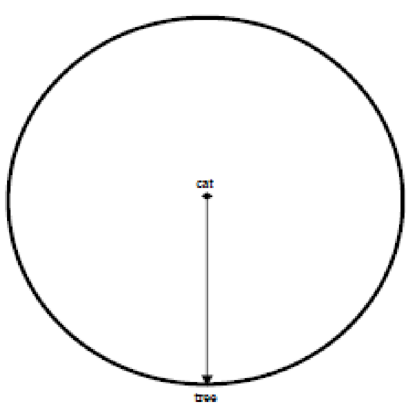


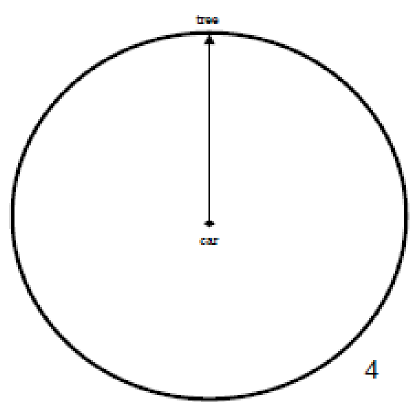
3



3. Imagine you are standing at the **cat** and facing the **tree**.
Point to the **car**.

4. Imagine you are standing at the **car** and facing the **tree**.
Point to the **house**.

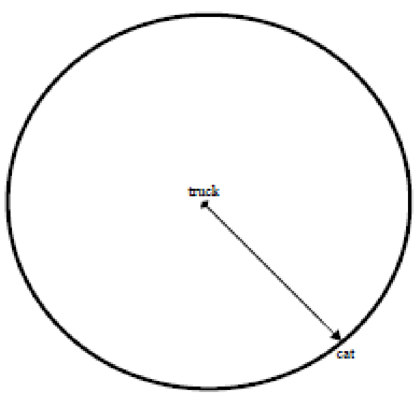


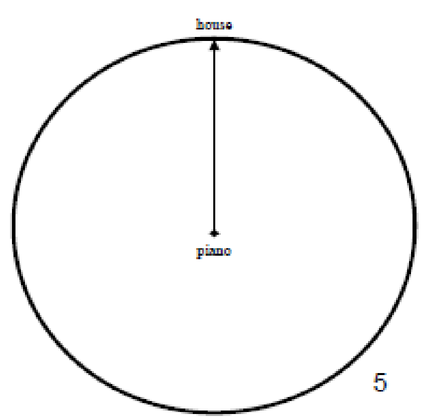


4

5. Imagine you are standing at the **truck** and facing the **cat**.
 Point to the **bird**.

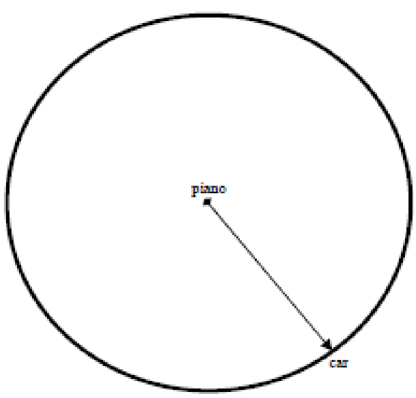
6. Imagine you are standing at the **piano** and facing the **house**.
 Point to the **tree**.



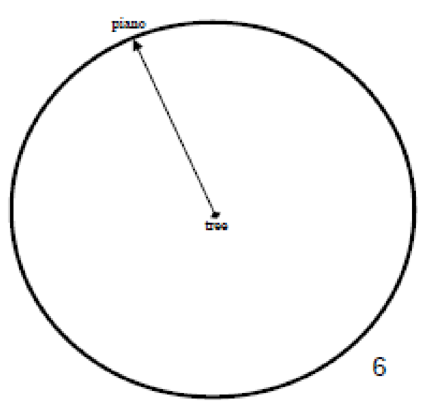


5

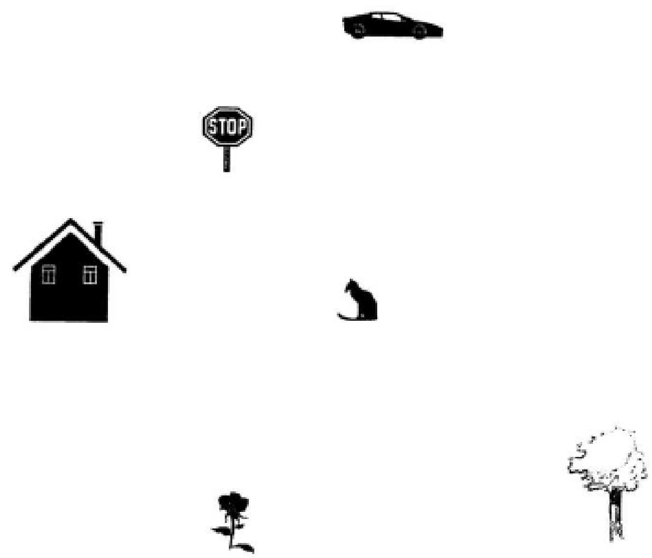
7. Imagine you are standing at the **piano** and facing the **car**.
Point to the **tree**.



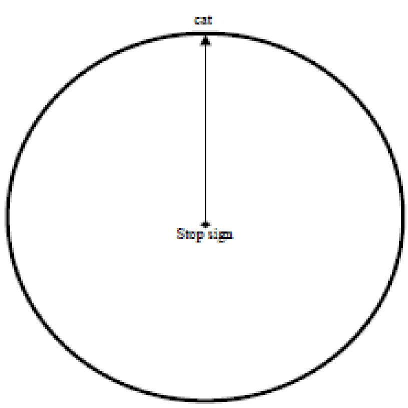
8. Imagine you are standing at the **tree** and facing the **piano**.
Point to the **car.**



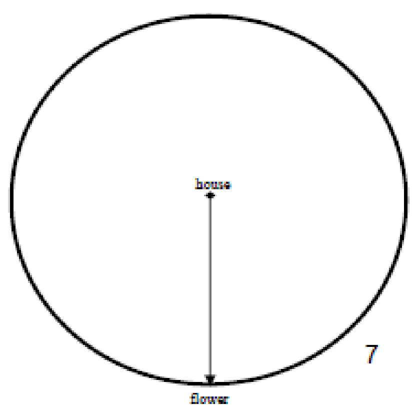
6



9. Imagine you are standing at the **stop sign** and facing the **cat**.
Point to the **house**.



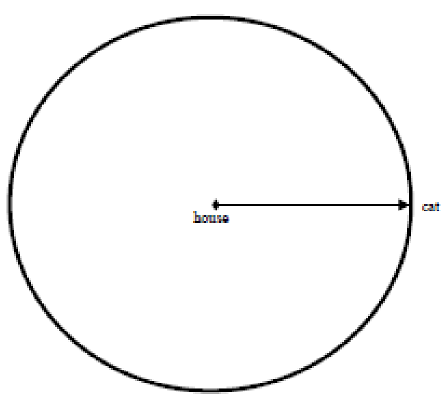
10. Imagine you are standing at the **house** and facing the **flower**.
Point to the **stop light**.

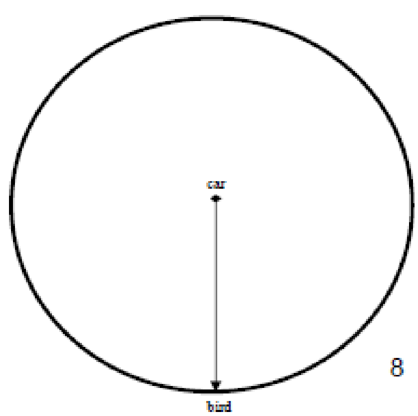


7

11. Imagine you are standing at the **house** and facing the **cat**.
Point to the **car**.

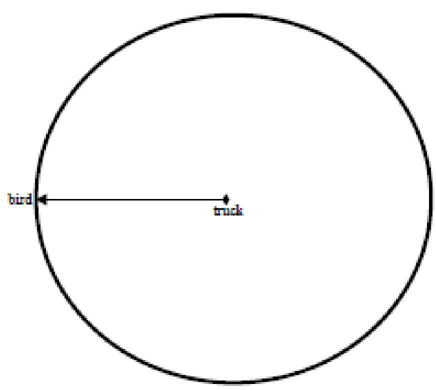
12. Imagine you are standing at the **car** and facing the **bird**.
Point to the **house**.



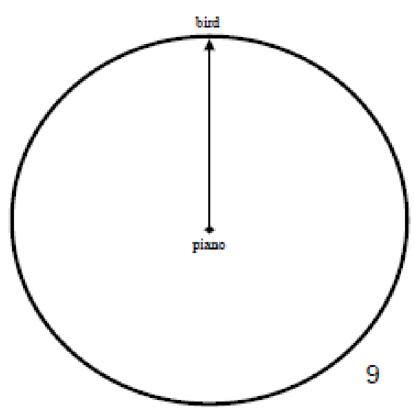


8

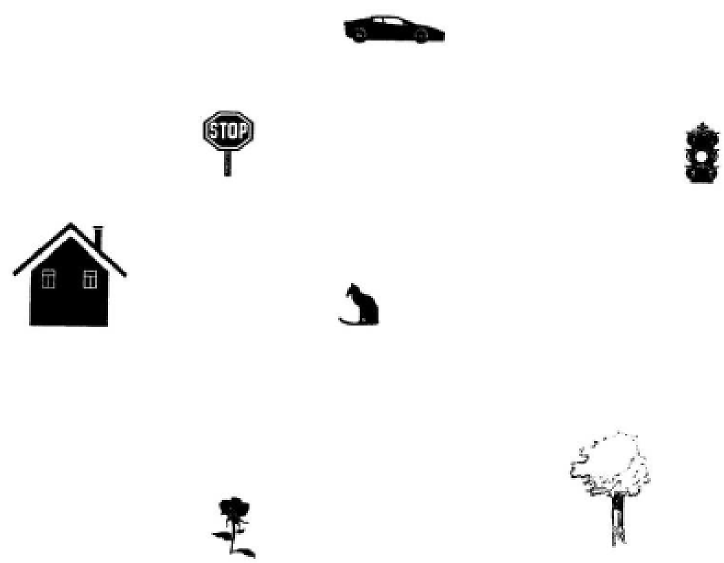
13. Imagine you are standing at the **truck** and facing the **bird**.
 Point to the **cat**.



14. Imagine you are standing at the **piano** and facing the **bird**.
 Point to the **truck**.

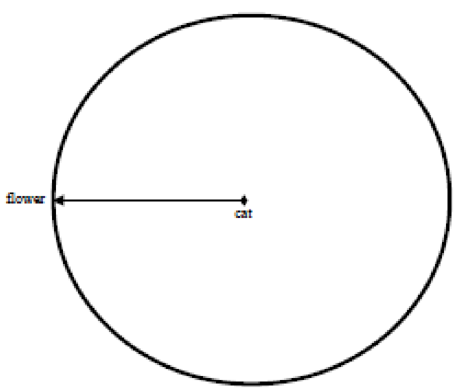


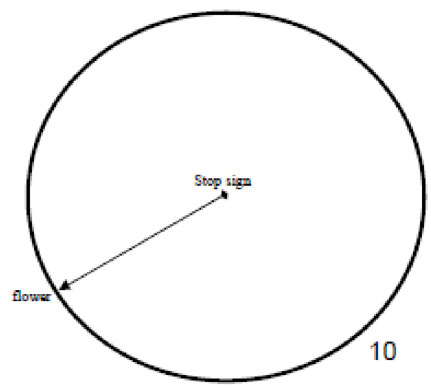
9



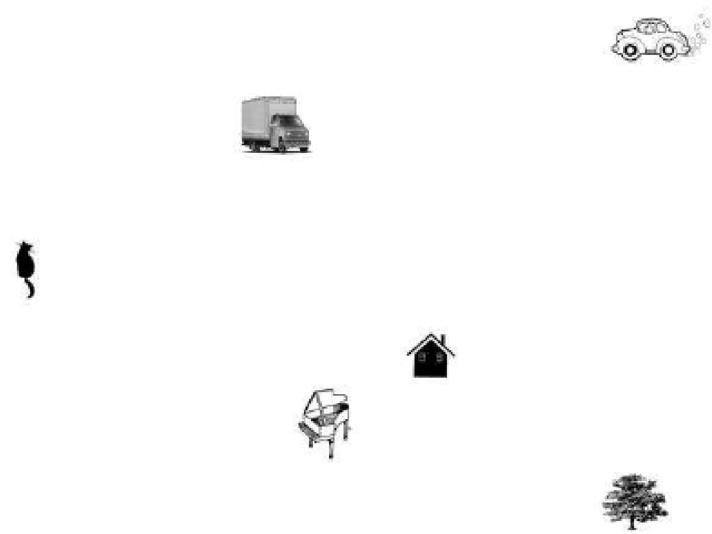
15. Imagine you are standing at the **cat** and facing the **flower**.
 Point to the **car**.

16. Imagine you are standing at the **stop sign** and facing the **flower**.
 Point to the **car**.



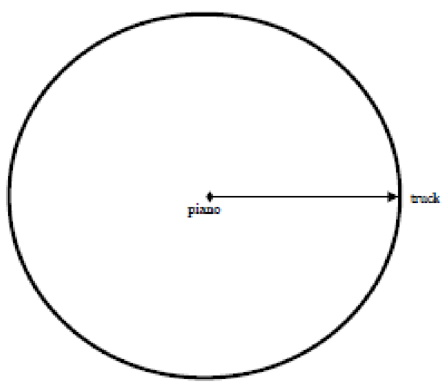


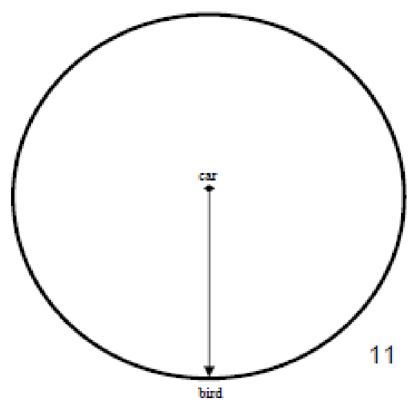
10



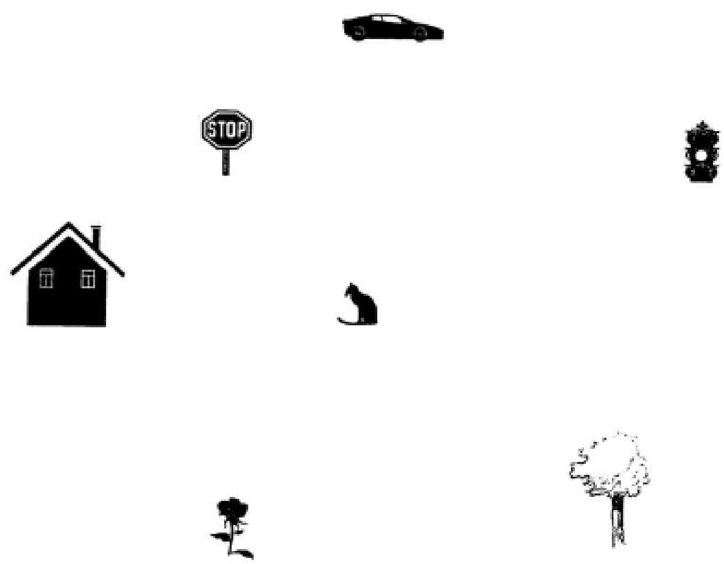
17. Imagine you are standing at the **piano** and facing the **truck**.
Point to the **tree**.

18. Imagine you are standing at the **car** and facing the **bird**.
Point to the **house.**



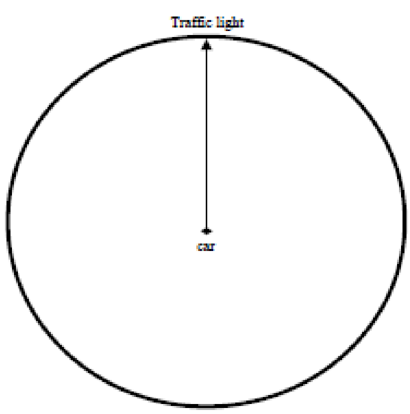


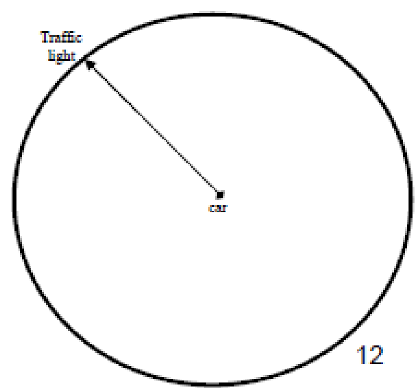
11



19. Imagine you are standing at the **car** and facing the **traffic light**.
 Point to the **stop sign**.

20. Imagine you are standing at the **car** and facing the **traffic light**.
 Point to the **flower**.





12

APPENDIX F

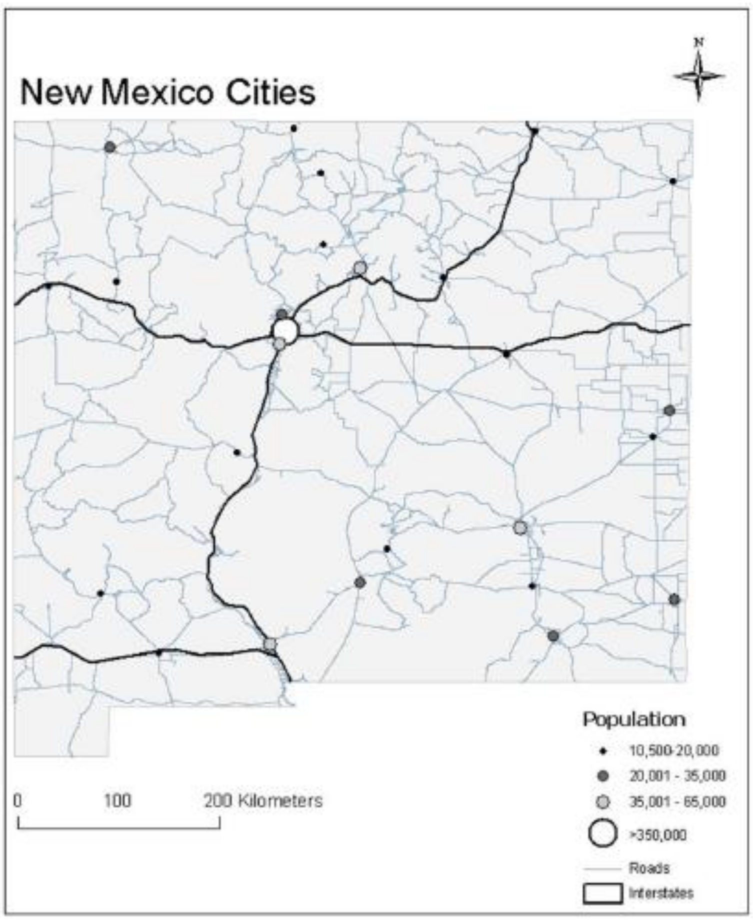
SPATIAL RELATIONS CONTENT KNOWLEDGE PRETEST

Research ID#: __________

Content Pre-Test

Use the images and maps to answer the set of questions that follow each image. Assume "region" applies to the area displayed in the referenced image or map.

Image 1:



1

_____ 1. Which of the following statements describing spatial patterns of market centers (cities) would be expected based on central-place theory and is supported by the actual distribution of cities in New Mexico as displayed above?

A. The larger in population size a city is, the greater the number of similar sized cities in the region.
B. The larger in population size a city is, the closer in distance that sized city will be to cities of similar population size.
C. The larger in population size a city is, the fewer the number of similar sized cities in the region.
D. The larger in population size a city is, the more difficult and costly transportation to that city will be.

_____ 2. Based on the spatial distribution of the cities displayed in the map above, you can infer that:

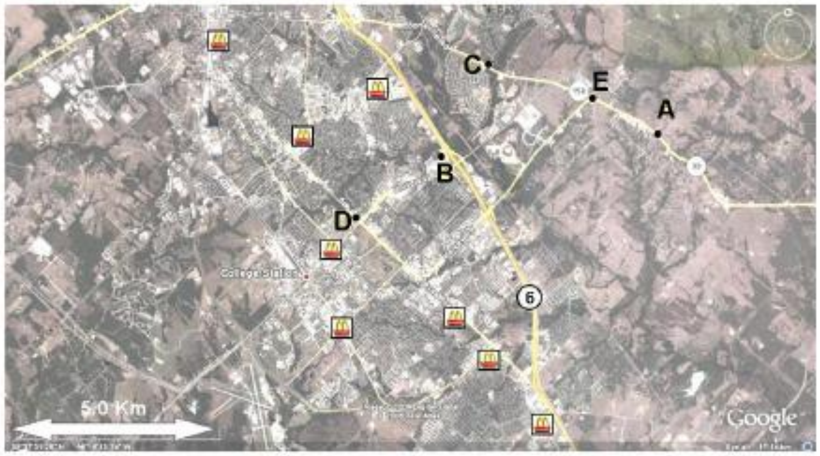
A. The terrain in this region is flat and homogeneous in most of the region.
B. The spatial distribution of market centers is even and regular.
C. Population is equally distributed throughout the region.
D. Population is concentrated along major transportation routes.

3. Imagine you are building a large convenient store called "Country Crossroads". As the name suggests, you want the store in a rural town where travelers from many directions are likely to converge.
Other criteria for location are **1)** in a small town (< 20,000), **2)** at least 100 km away from any town larger than 20,000, **3)** easy to drive to, and **4)** where people are most likely to pass through on their way to some place else.

Task: Determine the best location for the new store on the map above. Do not make any inferences beyond what can be inferred from the information provided on the map.
Circle the city on the map to indicate your first choice.

3

Directions: Below is a 'mashup' displaying the spatial pattern of McDonalds Restaurants in Bryan/College Station. The density of neighborhood streets in an area is a good indication of population. Use the image to answer the questions that follow.



_____ 4. The general spatial pattern displayed by the 8 McDonald's restaurants is:
- A. Random: there is no pattern to the restaurants' locations
- B. Linear: there is a general linear pattern from NW to SE
- C. Clustered: The restaurants are grouped
- D. Dense: There are many McDonalds located close together in a small area

_____ 5. Based on generalizations of spatial patterns in central-place theory which of the following could NOT be an explanation for the lack of McDonalds on the east side of Hwy 6 (in bold on the map)?
- A. Transportation costs are much higher based on time and traffic east of Hwy 6.
- B. People on the east side of Hwy 6 do not prefer to eat at fast food places
- C. The topography on the east side of Hwy 6 is flat with an evenly distributed population.
- D. There are very few central market centers to build the McDonald's next to on the east side of Hwy 6.

6. **Task**: Assume you are opening a new McDonald's Restaurant in the area. It must be close to a busy intersection and near other stores in an area of medium to high population. But, it cannot be placed within 1km of an existing McDonald's restaurant. **Circle the letter on the map to indicate the best location.**

4

APPENDIX G

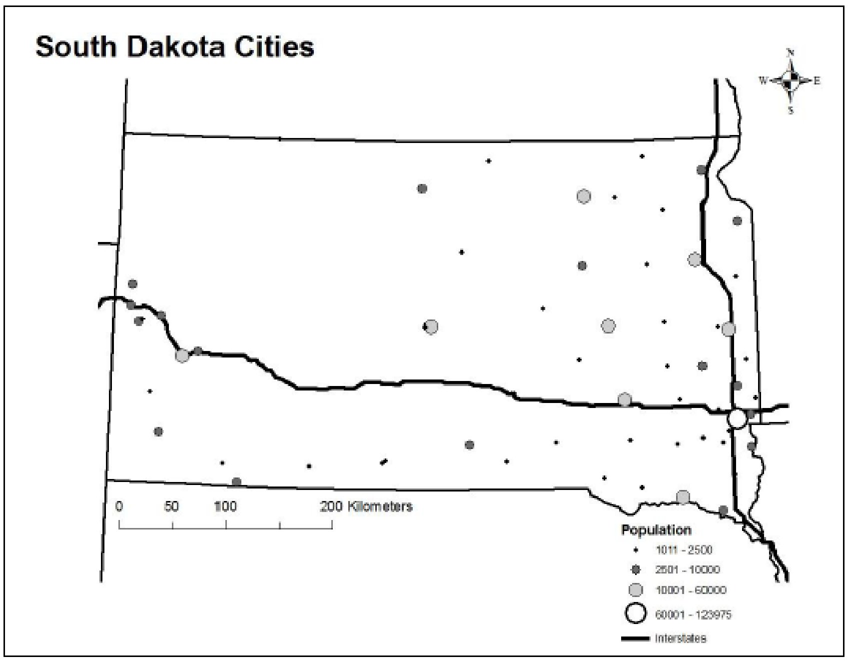
SPATIAL RELATIONS CONTENT KNOWLEDGE POSTTEST

Research ID#: __________

Content Post-Test

Use the images and maps to answer the set of questions that follow each image. Assume "region" applies to the area displayed in the referenced image or map.

Image 1:



1

_____ 1. Which of the following statements describing spatial patterns of market centers (cities) would be expected based on central -place theory and is supported by the actual distribution of cities in South Dakota as displayed above?

A. The larger in population size a city is, the greater the number of similar sized cities in the region.
B. The larger in population size a city is, the closer in distance that sized city will be to cities of similar population size.
C. The larger in population size a city is, the fewer the number of similar sized cities in the region.
D. The larger in population size a city is, the more difficult and costly transportation to that city will be.

_____ 2. Based on the spatial distribution of the cities displayed in the map above and on generalizations of central-place theory, you can infer that there are factors affecting the expected spatial patterns of market centers primarily in the:

A. NE corner of the state
B. NW corner of the state
C. SE corner of the state
D. SW corner of the state

_____ 3. All of the choices below are possible reasons for the departure from expected spatial patterns for the region identified in question 2 EXCEPT:

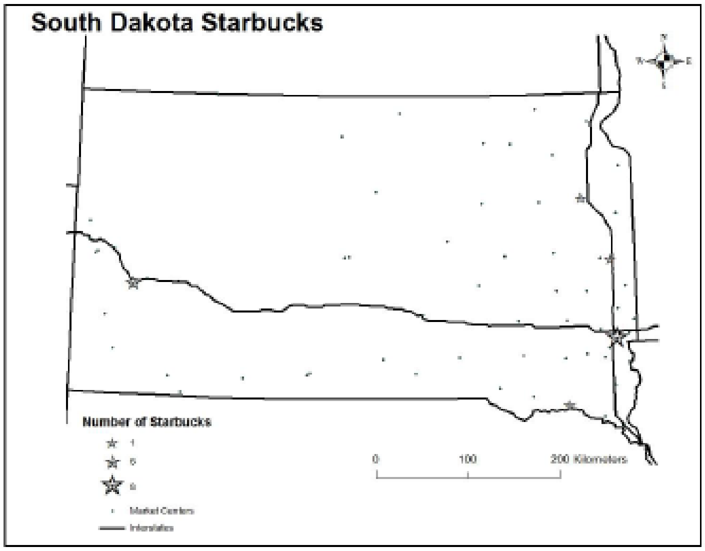
A. Topography or physical barriers
B. Human preference
C. Uneven distribution of wealth
D. Easy transportation in all directions

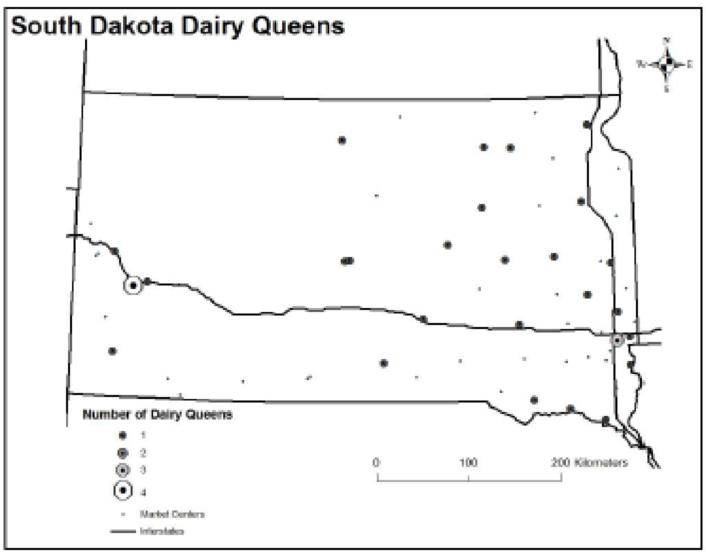
4. Imagine you are opening a new gas station.
You want the store in a medium sized town where travelers from many directions are likely to converge.
Other criteria for location are **1)** town size greater than 2,500, **2)** at least 50 km away from the interstate, and **3)** a location where people are most likely to pass through on their way to some place else.

Task: Using the generalizations of central-place theory determine the best location for the new gas station on the map above. Do not make any inferences beyond what can be inferred from the information provided on the map.

Circle the city on the map to indicate your first choice.

3


South Dakota Starbucks
Number of Starbucks
1
Market Centers
Interstates
0
100
200 Kilometers


South Dakota Dairy Queens
Number of Dairy Queens
1
2
3
4
Market Centers
Interstates
0
100
200 Kilometers

4

Directions: Above are two maps displaying the spatial distribution of Starbucks (top) and Dairy Queens (bottom) in South Dakota. Use these two maps in combination with the population map on page 1 to answer the questions below.

_____ 4. The general spatial pattern displayed by the Dairy Queen restaurants is:
A. Evenly spaced and distributed except in the northwest
B. Random: there is no pattern to the restaurants' locations except in the northwest
C. Clustered: The restaurants are grouped close together except in the northwest
D. Linear: Most of the restaurants are located close together along the interstates except in the northwest

_____ 5. Based on generalizations of spatial patterns in central-place theory which of the following could **NOT** be an explanation for the lack of restaurants in the NW?
A. Transportation costs are much higher based on time of travel in this region
B. People in the NW region do not prefer coffee or ice cream
C. There is too little population to provide the threshold needed for this order of goods
D. The topography in this region is flat and homogeneous

_____ 6. Based on central-place theory and the relative number of Starbucks to Dairy Queens, you can infer that:
A. Starbucks provides a higher order good as compared to Dairy Queen
B. Starbucks provides more expensive goods as compared to Dairy Queen
C. Starbucks requires a lower threshold than Dairy Queen to support its market
D. Starbucks' market areas are smaller than Dairy Queen's market areas

Task: Imagine you are the regional manager for Dairy Queen in South Dakota. Because of the weak economy, you must close one of the Dairy Queen stores.
The store you close must be in a town with only one exiting Dairy Queen. Other criteria are 1) a distance at least 50 km off the interstate but no more than 100 km, 2) the smaller the population of the town the better, and 3) a location where the least amount of travelers are likely to pass through.

Circle the Dairy Queen on the map to indicate the best location.

5

APPENDIX H

SANTA BARBARA SENSE OF DIRECTION SURVEY

Sense of Direction
Survey

Assigned Research #: __________

Date: __________

Please Circle or fill in your responses below:

Sex: F M

Age: ________

Dominant Hand: R L Equal/Both

This survey consists of several statements about your spatial and navigational abilities, preferences, and experiences. After each statement, you should circle a number to indicate your level of agreement with the statement. Circle "1" if you strongly agree that the statement applies to you, "6" if you strongly disagree, or some number in between if your agreement is intermediate.

1. I am very good at giving directions.

strongly agree 1 2 3 4 5 6 strongly disagree

2. I have a poor memory for where I left things.

strongly agree 1 2 3 4 5 6 strongly disagree

3. I am very good at judging distances.

strongly agree 1 2 3 4 5 6 strongly disagree

4. My "sense of direction" is very good.

strongly agree 1 2 3 4 5 6 strongly disagree

5. I tend to think of my environment in terms of cardinal directions (N, S, E, W).

strongly agree 1 2 3 4 5 6 strongly disagree

6. I very easily get lost in a new city.

strongly agree 1 2 3 4 5 6 strongly disagree

Source: Santa Barbara Sense of Direction Scale (SBSOD)
Hegarty et al (2002)

7. I enjoy reading maps.

strongly agree 1 2 3 4 5 6 strongly disagree

8. I have trouble understanding directions.

strongly agree 1 2 3 4 5 6 strongly disagree

9. I am very good at reading maps.

strongly agree 1 2 3 4 5 6 strongly disagree

10. I do **not** remember routes very well while riding as a passenger in a car.

strongly agree 1 2 3 4 5 6 strongly disagree

11. I do **not** enjoy giving directions.

strongly agree 1 2 3 4 5 6 strongly disagree

12. It is **not** important to me to know where I am.

strongly agree 1 2 3 4 5 6 strongly disagree

13. I usually let someone else do the navigational planning for long trips.

strongly agree 1 2 3 4 5 6 strongly disagree

14. I can usually remember a new route after I have traveled it only once.

strongly agree 1 2 3 4 5 6 strongly disagree

15. I do **not** have a very good "mental map" of my environment.

strongly agree 1 2 3 4 5 6 strongly disagree

16. I do **not** confuse right and left much.

strongly agree 1 2 3 4 5 6 strongly disagree

17. I tend to think visually, with lots of mental images.

strongly agree 1 2 3 4 5 6 strongly disagree

Source: Santa Barbara Sense of Direction Scale (SBSOD)
Hegarty et al (2002)

APPENDIX I

CSISD PERMISSION LETTER

College Station Independent School District

Success....each life....each day....each hour

February 20, 2009

Ms. Sandra Metoyer
808 South Ennis
Bryan, TX 77803

Dear Ms. Metoyer:

The College Station ISD Research Review Committee met today to review your research proposal and accompanying documentation. The committee chose to allow your research to be conducted in the district as it was proposed. Please make sure to contact Mr. Ernest Reed, the principal of A&M Consolidated High School, prior to beginning your data gathering.

If you should need any additional information, please contact my office at 764-5569.

Truly,

Clark C. Ealy, Ph.D.
Research Review Committee
College Station ISD

cc: Greg McIntyre
Research Review Committee
Ernest Reed

CLARK C. EALY, Ph.D.
Executive Director for Accountability and Planning

1812 Welsh Street
College Station, Texas 77840
979-764-5569 FAX 979-764-5425

EDDIE COULSON, Ed.D.
Superintendent of Schools

APPENDIX J

INSTRUCTOR SCRIPT

Day 2
Time Outline & Scripting

Class length = 50 minutes

Introduction:

1. Introduce yourself and your purpose. (1 minute)

Instructor:
"Hello. I am [redacted] from Texas A&M University. I am here to facilitate your activity today on central-place theory. The purpose of today's activity is to provide you with practice using spatial thinking skills and to test-out central-place theory by examining a real-world location's spatial patterns of market centers. You will use maps and tables to explore one of two European Countries, either Czech Republic or Belgium. You will have a hand-out to guide you."

2. Provide a brief review of prior day's class. (1 minute)

Instructor:
"Recall yesterday we [you] used maps to explore central-place theory. We outlined the basic premises of central-place theory. This included **assumptions** of the theory, **generalizations** about spatial patterns of market centers based on the assumptions, and factors that cause **exceptions** to expected spatial patterns of market centers." (1 minute)

3. Prompt the students to volunteer assumptions (4), generalizations (3), and factors that may cause alteration to expected spatial patterns (5+). They should have these listed on their own paper/notes from the prior class. (3 minutes)

Instructor:
"Remind me of the assumptions in central-place theory."

"And, what generalizations are made in central-place theory?"

"Recall the exceptions we [you] discussed yesterday. What are some factors that can alter the expected spatial pattern of market centers?"

4. Divide the class into 8 -10 groups of 2-3 students. Two is the preferred size, but actual groupings will depend on total number of students in the class. (3 minutes)

5. Pass one folder of maps to each group. Groups may choose the country assuming that choice is still available. There will be 5 folders for Belgium and 5 folders for Czech Republic. Remind students to NOT write on the maps. (3 minutes)

6. Referencing the maps, **describe spatial thinking strategies** that help geographers and scientists to interpret and analyze spatial patterns. (3 minutes)

1

Instructor:

"As you work through this activity, try to utilize spatial thinking strategies. Geographers look for patterns, arrays, and exceptions to spatially distributed phenomena. A strategy that helps us do this is imagining ourselves in a different place or orientation in the landscape. For example, as you look at a map you are looking down from above. What if you imagined yourself driving through the space on the interstate? You could 'see' the topography, imagine buildings, forest, or fields, and 'see' the changing population from a different orientation."

"As you explore the region, practice spatial thinking by asking yourself spatial orientation questions such as, "How would I see this pattern if I lived to the North versus some other direction?", or "What is the impact of a physical feature at ground-level that is only represented by a symbol on the map (ex. rivers look like thin lines on a map, but in the real-world can take up a large area.)?"

"A second spatial thinking strategy is mentally imagining an object or array of objects rotated or moved in some way. This is especially helpful when trying to see a spatial pattern of one thing when it is hidden or cluttered by other objects or features. As you explore the region, practice spatial thinking by mentally imagining only one feature at a time. For example, if you are interested in the spatial pattern of the smallest towns, you must exclude the symbols for larger towns in your mental picture of the area."

7. Give student groups the okay to begin the activity. You are available to answer questions and to facilitate. The activity is self-guided. Most of the questions are open-ended without one 'right' answer (although there is the possibility for wrong or poor answers). Each group may respond on one hand-out. Students should place all group member names on the hand-out. (25 -30 minutes)

8. 10 minutes prior to the end of class ask students to stop and place maps back into the folder for the next class. Encourage 2 or 3 groups to share their results. (5 minutes).

Instructor:

"Did the spatial pattern of market centers in your area (Czech Republic) support or refute central-place theory?"

9. Pass out homework assignment. The assignment is similar to what they did in class and has a rubric attached so the students know how the assignment will be scored. Homework is individual work and is due on Friday. (5 minutes)

APPENDIX K

STUDENT HANDOUT – INTERVENTION GROUP

Central Place Theory

Group Members:

____

____

Central Place Theory: Europe

The purpose of this activity is to test the assumptions and generalizations of central place theory for a country in Europe. You will use GIS layers in Google Earth to explore spatial patterns of market centers. You will work in pairs and may turn in your work on one answer sheet.

Population:
1. Load Google Earth (GE). Turn off all layers except for borders and roads. Go to "file", "open", and browse for the KML file titled, "Czech_cities."

2. Once opened, this KML file will fly you to Czech Republic. Notice the legend in the left tool bar showing folders labeled with population ranges.

3. Turn these layers on and off one at a time to explore the spatial patterns of the different sized cities.

4. Complete the following table:

Population size	Number of cities
Over 1 Million	
Between 200,000 and 500,000	
Between 90,000 and 200,000	
Between 50,00 and 89,000	
Between 25,000 and 50,000	

5. QUESTION:
Does the **ratio** (relative numbers) of big cities to small cities match what is expected based on central place theory? ________

6. QUESTION:
State a generalization of central place theory that best describes the pattern in the number of cities you counted for the table above.

____

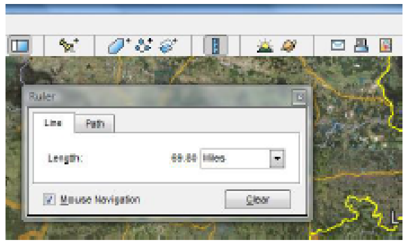
____

____

7. Turn off all the population layers except for cities with a population between 90,000 and 200,000.

8. Use the measure tool in GE to measure the distance between each one of the cities and the two cities closest to it.

1



9. QUESTION: What is the average distance between these market centers (cities)? Describe the spatial pattern of cities with population between 90,000 and 200,000. Are they evenly distributed? Elaborate.

____

____

____

10. Turn on only the top 3 population layers. Mentally imagine connecting each of the market centers (cities) together with straight lines.

11. QUESTION: Consider the "generalizations for central place theory. Does the spatial distribution of the larger cities in Czech Republic support central place theory? Is the shape you imagined for step 10 what you would expect? What is that shape? Elaborate.

____

____

____

12. Turn off all population layers except for the layer for cities with a population between 25,000 and 50,000.

13. Zoom in a little closer to a cluster of these small-population cities. Use the measuring tool to measure the distance between several of these smaller cities (not ALL, but at least 5-6 to get an average within a cluster).

14. QUESTION: What is the average distance between the smaller cities (25,000 – 50,000)? Is there more or less variation in the distances than there was with the large cities? Elaborate.

____

____

15. Turn on all 5 population layers. Examine the spatial patterns of the population distribution.

16. QUESTION: Overall, do the spatial patterns support central place theory? Is the theory supported in some cases, but not in others? Elaborate.

____

____

____

Higher Order versus Lower Order Goods:

1. Turn off the layers for population. Open a new KML file. Click on "File", and then select "Open". Browse for the KML file titled, "CzechMcD_Ttl."

2. Expand the folder for population "over 1 million" by clicking in the box with the "+" sign next to the folder labeled "over 1 million."

3. Double click on the title "Prague." You will automatically fly to Prague where McDonald locations are marked.

4. Notice the location and number of McDonald locations.

5. Repeat steps 2 through 4 for several cities within each size category and complete the table on the following page.

6. Complete the table below:

Population size	Number McDonald Restaurants
Over 1 Million	
Between 200,000 and 500,000	
Ex 1	
Ex 2	
Between 90,000 and 200,000	
Ex 1	
Ex 2	
Between 50,00 and 89,000	
Ex 1	
Ex 2	
Ex 3	
Between 25,000 and 50,000	
Ex 1	
Ex 2	
Ex 3	

7. QUESTION: What happens to the number of McDonald restaurants as the population size of the market center (city) decreases? Using central place theory as support, explain the relationship between population size and higher order versus lower order goods.

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8. QUESTION: Based on the numbers in the table above, estimate the population threshold needed to support a McDonalds restaurant in Czech Republic.

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SUMMARY: Are the assumptions and generalizations of central place theory supported by the spatial patterns of market centers in Czech Republic? Why or why not? Where and where not? What may have caused exceptions to the spatial patterns expected from central place theory?

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APPENDIX L

STUDENT HANDOUT – COMPARISON GROUP

Central Place Theory

Group Members:

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Central Place Theory: Europe

The purpose of this activity is to test the assumptions and generalizations of central place theory for a country in Europe. You will use maps to explore spatial patterns of market centers. You will work in pairs and may turn in your work on one answer sheet.

Population:

1. Take out the 5 separate population maps for Czech Republic. Each map illustrates the spatial distribution for different sized cities. Roads and topography are included on each map.

2. Use the maps to complete the following table:

Population size	Number of cities
Over 1 Million	
Between 200,000 and 500,000	
Between 90,000 and 200,000	
Between 50,00 and 89,000	
Between 25,000 and 50,000	

3. QUESTION:
Does the **ratio** (relative numbers) of big cities to small cities match what is expected based on central place theory? ________

4. QUESTION:
State a generalization of central place theory that best describes the pattern in the number of cities you counted for the table above.

____

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5. Look at the map displaying cities with a population between 90,000 and 200,000. Imagine where Prague would be located among these cities.

1

6. Use a ruler and the scale bar to **estimate** the distance between each one of the large cities and the two cities of the same size closest to it. Complete the table below:

Measure city to city	Map Distance	Real-world distance
1. (Ex) Budweis to Plizen		
2		
3.		
4.		
5.		
6.		
7.		

7. QUESTION: Estimate the average distance between these market centers (cities) from your measurements in the table above. Describe the spatial pattern of cities with population between 90,000 and 200,000. Are they evenly distributed? Elaborate.

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8. Look at the following maps; over 1 million, between 200,000 and 500,000, and between 90,000 and 200,000. Mentally imagine connecting each of the market centers (cities) together with straight lines.

9. QUESTION: Consider the "generalizations for central place theory. Does the spatial distribution of the larger cities in Czech Republic support central place theory? Is the shape you imagined for step 8 what you would expect from central place theory? What is that shape? Elaborate.

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10. Look at the map displaying population between 25,000 and 50,000.

11. Select one cluster of these small-population cities. Use a ruler and scale bar to measure the distance between several of these smaller cities (not ALL, but at least 5-6 to get an average within a cluster).

12. QUESTION: **Estimate** the average distance between the smaller cities (25,000 – 50,000)? Is there more or less variation in the distances than there was with the large cities? Elaborate.

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13. Examine all 5 population maps. Examine the spatial patterns of the population distribution.

14. QUESTION: Overall, do the spatial patterns support central place theory? Is the theory supported in some cases, but not in others? Elaborate.

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Higher Order versus Lower-Order Goods:

1. Examine the map titled, "McDonalds."

2. Notice the general location and number of McDonald locations in Czech Republic.

3. Examine the table displaying city name, population, and number of McDonald restaurants.

4. Complete the table below:

Population size	Number McDonald Restaurants
Over 1 Million (Prague)	
Between 200,000 and 500,000	
Ex 1:	
Ex 2:	
Between 90,000 and 200,000	
Ex 1:	
Ex 2:	
Between 50,00 and 89,000	
Ex 1:	
Ex 2:	
Ex 3:	
Between 25,000 and 50,000	
Ex 1:	
Ex 2:	
Ex 3:	

5. QUESTION: What happens to the number of McDonald restaurants as the population size of the market center (city) decreases? Using central place theory as support, explain the relationship between population size and higher order versus lower order goods.

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____

6. QUESTION: Based on the numbers in the table, estimate the population threshold needed to support a McDonalds restaurant in Czech Republic.

____

SUMMARY: Are the assumptions and generalizations of central place theory supported by the spatial patterns of market centers in Czech Republic? Why or why not? Where and where not? What may have caused **exceptions** to the spatial patterns expected from central place theory?

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APPENDIX M

OBSERVER NOTES

Observation Notes: Observer 1

<u>Period 2: 09:15 am – 10:10 am</u>

Activities in the computer lab (observed from 09:20 to 09:45)

- Instructor reminded students of the Central Place Theory from yesterday's class. Students seemed to remember some of the assumptions and generalizations although they were not able to speak them out completely by themselves.
- Students were asked to answer questions in the worksheet provided, using Google Earth maps and information on the maps.
- Students looked pretty good at manipulating Google Earth functions required for the activity.
- Students discussed to answer the questions
  - Concepts discussed
    - distance (e.g., smallest, largest, and average distance)
    - shape (e.g., pentagon)
    - close to each other (indicates concept of 'cluster')
  - (Cognitive) behaviors observed
    - Students used just two distances – smallest and largest - to get the approximate average distance (applying formula although modified for convenience)
    - Students recognized that smaller cities are closer to each other than are larger cities (comparing features)
    - Students kept zooming in/out to get the best resolution to see the patterns looked for (executing, applying functions)
    - Students talked to each other to figure out some of the functions of Google Earth which gave them different displays (comparing, applying, generalizing)

While students were working on page 4-5 of the worksheet, I left for the other classroom.

1

Observation Notes: Observer 1

Activities in the classroom (observed from 09:45 to 10:05)

- Students were working on the table (# of cities having specific size of population) in the worksheet (I don't remember the page but almost last part before summary).
- Students seemed to think that the questions pretty straightforward and not confusing.
- There was not much discussion in the group that I joined. The girl kept reading questions aloud and asking how her partner thought about that, but the partner did not seem very enthusiastic.
- Despite lack of discussion, the summary of the activity included major spatial concepts such as spatial patterns, cluster, and distance, which indicates that students grasped basic ideas underlying Central Place Theory.

I wish I could have observed two ENTIRE classes rather than half and half. The comparison can't be done in a systematic way because of the differences in questions on which students in each group were working…

2

Observation Notes: Observer 2

Observation Result

- **Overall impression**

1. Students are not using spatial terms frequently. Students' spatial terms are confined to those used by the instructor or written on the material. The students in the experiment group seemed to be using spatial terms a little bit frequently, but the difference was not significantly huge. The reason could be: 1) The experiment was conducted during a short period of time, 2) Hence, individual differences could be affecting more.
2. Students in the experiment group are more active than in the control group. The students in the experiment group appeared to be more excited or interested in the activities. The reason could be either the effectiveness of technology or novelty of the experiment situations.
3. Students in the experiment group could figure out the shape more effectively and dynamically than those in the control group.
4. The experiment group appears to have an 'unintended effect' by manipulating map scale (I'm not sure what word I should use; this could be both positive or negative effects. Personally, this seems to be a positive aspect of using GE). In changing scale, students were discussing a '*border*' and '*shap*e' of features and utilization of land, which were not required activities. This kind of behavior could contribute to enhancing students' interest and understanding about geography, but also could distract students. At any rate, this kind of activity made students use more spatial terms.
5. Even in the same condition (i.e., in the same experiment group or control group), the frequency of spatial terms use differs from group to group. This indicates that individual differences could be one important factor in using of spatial term. However, I think it is difficult to deal with every individual difference under this experimental design.
6. I observed only six groups (three experiment groups, three control groups). This means that the sample size is small, so the observation cannot be generalized with confidence.

- **Spatial terms used by each group:**

Because students were not using spatial terms frequently and iteratively, it was difficult to count the frequency of each spatial term. Hence spatial terms used by the students are recorded at an aggregated level.

- Experiment group

1

Observation Notes: Observer 2

1. Geometry related terms such as *hexagon* and *triangle* were used relatively frequently. This could be because those terms were introduced in the previous lecture about Central Place Theory. Students were using those terms when they judged the shape made by connecting cities.
2. The assumption related terms were used: large *city*, easy *access*, *travel, direction, flat, uniform, population, population density, huge city, located in the center, clusters*
3. One active group was using relatively many spatial terms that were not used by other groups frequently: *spatial variation, connect, closer, annual, small cities close, city center, annual, middle, clustered but not evenly distributed, mountainous*
4. Computer related (or scale-related) terms were used: *zoom-in, zoom-out*

- Control group

1. Geometry related terms used as well in the same manner as in the experiment group. But the frequency appears to be a little bit low. I think this is because the students in the control group cannot change scale. The students in the experiment group were meeting changing patterns (or shape) when they manipulated the map scale.
2. Distance measurement related terms were used: The control group measured the distance in a different manner than the experiment group. When they measure the *distance*, they should set the reference point such as a *starting point* and *edge of the shape*.
3. One active group was using relative difficult terms: *heterogeneous, pattern, scattered*

2

APPENDIX N

DESCRIPTION OF CENTRAL PLACE THEORY

Terms:

"Central place theory attempts to explain the location, size, characteristics, and spacing of clusters [markets] of [economic] activity. It is, therefore, the descriptive and theoretical base of the geography of retail and service businesses (Berry and Parr 1988)."

Market places are locations with social, economic, and cultural referents where buyers and sellers exist and where exchange takes place.

History:

Central place theory was developed by German geographer Walter Christaller to explain the spatial dispersion of economic activity in Germany. The theory was outlined in his book published in 1933 (*Die zentralen Orte in Süddeutschland*) and translated to English by Baskin (1966).

Simplifying assumptions:

- A flat, homogeneous, and limitless physical surface
- An evenly distributed population and resources
- All individuals are able to make purchases on an equal basis
- Supply and demand for goods and services is similar across the region
- Transportation is easy and accessible in all directions
- The cost of transportation increases with distance away from the market center

Christaller identified three generalizations about spatial distribution of settlements in southern Germany (Favier 2011, 144-146):

1. Settlements [market centers] can be classified by the size of the population; large cities, small cities, and villages.
2. There are more villages than small cities. There are more small cities than large cities.
3. Distances among settlements of a similar size tend to be equal and form a repeating geometric pattern of regular hexagons.

These generalizations are measurable and were used to investigate central place theory, for this intervention study, in the Czech Republic.

Factors that may affect the spatial dispersion of market centers:

- Non-valid simplifying assumptions
- Topography
- History of development
- Technology
- Human preference or choice
- Relative wealth, or lack of, within a city

References:

Berry, B. and J. Parr. 1988. *Market Centers and Retail Location: Theory and Applications* Englewood Wood Cliffs, NJ: Prentice-Hall Inc.

Christaller, W. 1966. *Central Places in Southern Germany*. Translated from *Die zentralen Orte in Süddeutschland* by C. W. Baskin. Englewood Cliffs, NJ: Prentice-Hall Inc.

Favier, Tim. 2011. Geographic information Systems in inquiry-based secondary geography Education. Ph.D. Dissertation. VU University Amsterdam, Amsterdam, the Netherlands: Ipskamp. ISBN No. 978-94-6190-105-7.

APPENDIX O

CURRICULUM VITAE

Curriculum Vitae
Sandra K. Metoyer

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979-204-1147

EDUCATION

A.B.D.	Texas A&M University (Geography) Expected Graduation Date – December 2014 Committee Chair: Dr. Robert Bednarz Dissertation Title: Geospatial technology: A tool to enhance spatial thinking skills and facilitate processes of reasoning	**2014**
M.S.	Texas A&M University (Geoscience)	**2005**
B.S.	University of Texas – Arlington (Biology)	**1990**

PROFESSIONAL EXPERIENCE

Research Associate, Education Research Center at Texas A&M University	**Mar 2013 – 2014**
Assistant Professor, College of Education, Department of Curriculum & Instruction, Texas A&M University Corpus Christi	**2011 – Aug 2012**
Director – College and Career Readiness Initiative's Science Faculty Collaborative, Texas Higher Education Coordinating Board (THECB), Texas A&M University Corpus Christi	**2010 – 2012**
Director – Coastal Bend Regional Science Fair, College of Education, Texas A&M University Corpus Christi	**2010 – 2012**
Geography Lecturer, World Regional Geography, Geography Department, Texas A&M University	**Summer 2010**
National Science Foundation Graduate Research Fellow, Graduate STEM Fellows in K-12 Education Program (GK-12), Advancing Geospatial Skills in Science and Social Science (AGSSS), Geography Department, Texas A&M University	**2007-2010**
National Science Foundation Graduate Research Fellow, Information Technology in Sciences: Center for Learning and Teaching (ITS-CLT). College of Science and College of Education, Texas A&M University	**2003-2007**
Classroom Teacher, Texas	**1998-2003**

COURSES TAUGHT

- Environmental Science for the EC-12 Multicultural Classroom – EDCI 4390/5390 Study abroad course in Costa Rica at the Texas A&M Soltis Center for Research and Education
- Methods for Teaching Science – EDCI 5317 at Texas A&M University Corpus Christi
- Special Populations – EDCI 4321 at Texas A&M University Corpus Christi
- World Regional Geography – GEOG 0202 at Texas A&M University
- Secondary (grades 7-12th) Sciences: Aquatic Science, Introduction to Physics & Chemistry, Biology. Chemistry, Environmental Science, and Integrated Science

GRANT PROPOSALS (Funded)

Researcher and Author **2013**
International Baccalaureate Organization, Principal Investigator: Jacqueline Stillisano, Funded for 2013-2015, $50,000, *Student Reflection: A Mixed method study of 'Reflective' in the IB Diploma Programme.*

Principal Investigator and Author **2011**
Texas Higher Education Coordinating Board, College and Career Readiness Initiative, Principal Investigator: Sandra Metoyer, Funded for 2011-2013, $99,930, *Science Faculty Collaborative regional workshops and culminating conference.*

Principal Investigator and Author **2011**
Texas Higher Education Coordinating Board, College and Career Readiness Initiative, Principal Investigator: Sandra Metoyer, Funded for 2011-2013, $99,543, *Improving college science success by integrating College and Career Readiness Standards in math and science: A transportable and diffusible professional development model.*

GRANT PROPOSALS (Submitted – Funding Declined)

Researcher and Author **2013**
Texas Higher Education Coordinating Board's Texas Fund for Geography Education, Principal Investigator: Hersh Waxman, $39,586, *Inspiring geographic practices with team-based learning.*

Researcher and Author **2013**
International Baccalaureate Organization, Principal Investigator: Jacqueline Stillisano, $55,000, *Examination of district-wide IB implementation in the United States.*

Principal Investigator and Author **2011**
Office of Naval Research STEM for K-12 & Institutions of Higher Education, Principal Investigator: Sandra Metoyer, $681,750, *V-FAIR for STEM: a Vehicle to foster achievement using IT and research for STEM education.*

Director and Author **2011**
National Science Foundation, Innovative Technology Experiences for Students and Teachers (ITEST), Principal Investigator: Arthur Hernandez, $988,120, *V-FAIR for STEM: a Vehicle to foster achievement using ICT and research for STEM education.*

Co-Investigator and Co-Author **2010**
Institute for Education Sciences, Cognition and Student Learning, Principal Investigator: Robert Bednarz, $1,167,817, *Spatial Cognition: Foundations for Student Learning in the Geosciences* (revised from a 2009 submission to IES).

PUBLICATIONS

Metoyer, S. (in preparation). Geospatial Technology: Enhancing spatial thinking skills and facilitating processes of reasoning. Target publication: *Journal of Geography.*

Metoyer, S., Miller, S., Mount, J., & Westmoreland, S. (2014). Team-based learning™: Collaborative work that works to inspire critical thinking and engagement. *Journal of College Science Teaching, 43*(5), 40-47.

Medina, S., Ortlieb, E., & **Metoyer S.** (2014). Life science literacy of an undergraduate population. *The American Biology Teacher,* 76(1), 34-41.

Metoyer, S. (2011). Southeast Asia: Web-based GIS and Graphs to Explore Patterns of Demographics and Disease. *The Geography Teacher,* 8(1), 42-49.

Walkington, H., Griffin, A., Keys-Matthews, L., **Metoyer, S.**, Miller, W., Baker, R., & France, D. (2011). Embedding research-based learning and inquiry in the undergraduate geography curriculum. *Journal of Geography in Higher Education,* 35(3), 1-16.

Metoyer, S. (2010). Behavioral Geography. Entry for *Encyclopedia of Geography*, Ed. Barney Warf. SAGE Reference Publications.

Jo, I., Bednarz, S.W., & **Metoyer, S.** (2010). Designing questions to facilitate spatial thinking. *The Geography Teacher,* 7(2), 49-55.

Bednarz, S.W., Bednarz, R. & **Metoyer, S.** (2009). The Importance of thinking spatially: Introducing spatial thinking in geography education. Proceedings from the 6th International Conference on Geographic Information Systems (ICGIS-2009), Tokyo, Japan.

Martinez, A., Williams, N., **Metoyer**, S. & Berhane, S. (2009). A Geospatial scavenger hunt. *Science Scope,* 32(6), 18-23.

TECHNICAL REPORTS

Wright, K. B., Kandel-Cisco, B., Hodges, T. S., **Metoyer, S.**, Boriack, A. W., Stillisano, J. R., & Waxman, H. C. (2013, December). *Developing and assessing students' collaboration in the IB programme*. College Station, TX: Education Research Center at Texas A&M University. Submitted to the International Baccalaureate Organization (IBO).

Stillisano, J. R., **Metoyer, S.**, & Brown, D. B. (2013, August). *Evaluation of Mitchell Institute Physics Enhancement Program (MIPEP) Summer Institute*. College Station, TX: Education Research Center at Texas A&M University. Submitted to the Mitchell Institute.

Stillisano, J.R., Brown, D.B., Wright, K.B., **Metoyer, S.**, Hodges, T.S., Rollins, K.B., & Waxman, H.C. (2013, August). *Evaluation of College Readiness Assignments Field Test* (CRAFT). College Station, TX: Education Research Center at Texas A&M University. Submitted to the Texas Higher Education Coordinating Board (THECB).

Metoyer, S. (2012, February). *The College and Career Initiative Faculty Collaboratives: Project Director's Full Report.* Submitted to the Texas Higher Education Coordinating Board (THECB).

GRADUATE THESES – Mentor

Graduate Students mentored on their thesis:

Stephanie Medina, M.S. (2011, December). Texas A&M University Corpus Christi. Title: *Life science literacy of an undergraduate population.*

Ibet V. Caro, M.S. (2012, May). Texas A&M University Corpus Christi. Title: *The Effects of reviewing mathematical concepts in a conceptual chemistry classroom.*

Leslie Startz, M.S. (2012, May). Texas A&M University Corpus Christi. Title: *Finding a balance between instructional methods in seventh grade science classroom.*

INVITED PRESENTATIONS/WORKSHOPS

Metoyer, S. (2014, May & 2013, November). *Inspiring inquiry using team-based learning.* Workshop presented to Blinn College faculty. Bryan, TX. November 1, 2013.

Metoyer, S. (2013, May). *Strategies for teaching college classes with team-based learning and College and Career Readiness Standards.* Workshop presented to Social Studies Faculty Collaborative. Bryan, TX. May 11, 2013.

Metoyer, S. (2012, December). *Planning backwards: Designing assessment for team-based learning.* Social Studies Faculty Collaborative Symposium. Grapevine, TX. December 1, 2012.

Metoyer, S. (2011, November). *Classroom strategies to improve the quality of student-directed science fair projects.* Diocesan Catholic Educators Conference. Corpus Christi, TX. November 2011.

Metoyer, S. (2011, September). *Increasing College and Career Readiness in the sciences through discipline-specific instructional strategies for scientific literacy.* College and Career Readiness Initiative: English/Language Arts Faculty Collaborative Symposium. Austin, TX. September 15, 2011.

Metoyer, S. (2011, May). *Evidence: High spatial skills enhance learning of geographic concepts.* Biannual Grosvenor Center Conference on Research in Geographic Education. Lafayette, LA. May 18, 2011.

Metoyer, S. & Jo, I. (2009, May). *Explicit teaching strategies for spatial thinking skills.* Geosummit: An International Symposium on Teaching and Learning in Geography. Gilbert M. Grosvenor Center for Geographic Education, Texas State University – San Marcos. May 28, 2009.

Bednarz, R., Jo, I. & **Metoyer, S.** (2008, November). *Spatial thinking research at Texas A&M.* Spatial Learning in Geography Workshop. Hosted by National Geographic Society and the Spatial Intelligence and Learning Center, Washington, D.C. November 8, 2008.

SELECTED PRESENTATIONS

Metoyer, S. (2013, November). *College Readiness for success in the sciences*. Conference for the Advancement of Science Teaching (CAST), Houston, TX, November 8, 2013.

Metoyer, S. (2012, October). *Inspiring geographic inquiry using team-based learning (TBL)™.* National Council for Geographic Education (NCGE), San Marcos, TX, October 6, 2012.

Metoyer, S., Miller, S., Mount, J., & Westmoreland, S. (2011, October). *Preparing preservice science teachers using team-based learning strategies and the College and Career Readiness Standards for science*. Southwest Association for Science Teacher Educators (SW-ASTE). Lubbock, TX, October 2011.

Metoyer, S. & Barnes, S. (2011, October). Texas College and Career Readiness Initiative: Faculty Collaboratives with a focus on the Science Faculty Collaborative. Consortium of State Organizations for Texas Teacher Education (CSOTTE). Corpus Christi, TX, October 2011.

Metoyer, S. (2011, April). *Community at the Festival: Social spaces created among the strange and the deviant*. Association of American Geographers (AAG) Annual Meeting. Seattle, WA, April 2011.

Metoyer, S. (2011, February). *Integrating Mathematics and Science College and Career Readiness Standards: Suggested approaches*. Texas Alternative Certification Association (TACA). Dallas, TX. February 2011.

McCollough, C., & **Metoyer, S.** (2011, February). *College Readiness: Preparing science educators for closing the gaps in participation and success in science*. Annual meeting for the Southwest Educational Research Association (SERA). San Antonio, TX. February 3, 2011.

Metoyer, S. (2010, April). *Geovisualization tools and spatial cognition: Exploring interactions among geovisualization tools, spatial thinking, and student learning*. Association of American Geographers (AAG) Annual Meeting. Washington D.C., April 15, 2010.

Metoyer, S. (2009, November). *Geospatial Technology: Enhancing spatial thinking skills and facilitating processes of reasoning*. College and University Faculty Assembly of the National Council for the National Council of Social Studies (NCSS) Annual Meeting. Atlanta, GA. November 12, 2009.

Metoyer, S., & Jo. I. (2009, March). *Instruction in spatial thought: Effects of explicit strategies on spatial thinking skills*. Association of American Geographers (AAG) Annual Meeting. Las Vegas, NV, March 26, 2009.

Horn, S., Harbor, J., Bednarz, S. W., **Metoyer**, S., Taylor, Z., & Valente, M. (2009, March). *What is an NSF GK-12 grant and how would getting one help me and my department?* Panel Session at Association of American Geographers (AAG) Annual Meeting. Las Vegas, NV, March 25, 2009.

Metoyer, S., & Lemmons, K. (2008, October). *Integrating spatial thinking skills and content.* National Conference on Geography Education (NCGE). Dearborn, MI. October 10, 2008.

Metoyer, S. (2008, April). *The Hierarchical Parallel Model (HP-Model) of spatial cognition: Integration of neuroscience and education to improve spatial thinking and geographic literacy*. Association of American Geographers (AAG) Annual Meeting, Boston, MA, April 17, 2008.

Metoyer, S., Prouhet, T. & Radencic, S. (2007, December). *Creating science education specialists and scientific literacy in students through a successful partnership among scientists, science teachers, and education researchers*. American Geophysical Union (AGU) Fall Meeting – poster session, San Francisco, CA, December 11, 2007.

Williams, N., **Metoyer, S.**, Martinez, A., Berhane, S. & Kincaid, J. (2007, December). *Advancing geospatial technologies in science and social science: A case study in collaborative education.* American Geophysical Union (AGU) Fall Meeting – poster session, San Francisco, California. December 11, 2007.

Metoyer, S., Hilding-Kronforst, S. & Schielack, J. (2006, April). *Identifying leadership development as a critical component of the ITS transportable model: Impacts of ITS on and by science and science education graduate assistants*, in Critical components for producing new leadership in science education, Chair Jane Schielack. American Education Research Association Annual (AERA) Meeting. San Francisco, CA, April 8, 2006.

Metoyer, S. (2006, April). *Impacts of the ITS Center on innovative use of IT, in scientific inquiry and IT*: Catalysts for an innovative professional development model for graduate students and teachers, Chair Carol Stuessy. American Education Research Association (AERA) Meeting. San Francisco, CA, April 8, 2006.

Metoyer, S. (2005, February). *Dynamic Osmosis: The effects of static modeling compared to dynamic computer modeling in the study of osmosis on student understanding and knowledge transfer.* NSF PI annual meeting (CLT), Washington DC, NSF, February 11, 2005.

INTERNATIONAL FIELD EXPERIENCE

- San Isidro, Costa Rica. Course design, implementation, and science perspective research for *Environmental Science for the EC-12 Multicultural Classroom* at the Soltis Center for Research and Education. May 2012.
- San Isidro, Costa Rica. Field surveying and mapping for construction of the Soltis Center for Research and Education. August 2008, January 2008, and January 2007.
- Busan, South Korea. Cultural exploration of spatial thinking among secondary students. June 2008.

SERVICE EXPERIENCE

- Director for the Coastal Bend Regional Science Fair (CBSF) 2011 and 2012
- Reviewer for *Journal of Geography*
- Reviewer for *Journal of Geoscience Education*
- Reviewer for American Education Research Association conference proposals, Division C
- Elected board member and evaluator for 2011and 2012 AAG Gail Hobbs Student Paper Competition (AAG – Geography Education Specialty Group)
- Executive Planning Board Member – Publications Committee for NCGE, 2011 – 2013

TEACHING EXPERIENCE

- Assistant Professor. (2011-2012). Teaching Emphasis: Science and Geographic Education in the Department of Curriculum & Instruction, Texas A&M University Corpus Christi.
- Lecturer for World Regional Geography. (2010). Geography Department, Texas A&M University.
- Teaching and Research Assistant. (2007- 2010). NSF GK-12 Project: Advancing Geospatial Skills in Science and Social Science. College of Geosciences, Texas A&M University.
- Teaching and Research Assistant. (2005 – 2007). Information Technology in Sciences: Center for Learning and Teaching. College of Science & College of Education, Texas A&M University.
- Physical Geography Lab. (2004 – 2005). Department of Geography, Texas A&M University.
- 7th grade Integrated Science. (2000-2003). Bryan ISD, Texas.
- Aquatic/Environmental Science, Biology, and Chemistry. (1999-2000). Alta Vista Private Academy, College Station, Texas.
- Aquatic/Environmental Science. (1998-1999). Brenham ISD, Texas.

MEMBERSHIPS

- American Educational Research Association
- Association of American Geographers
- National Association for Research in Science Teaching
- National Council for Geographic Education
- Science Teachers Association of Texas